

CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Gothenburg, Sweden
Telephone: +46-(0)31 772 10 00
www.chalmers.se



Towards Technology Assessment of Ocean Energy in a Developing Country Context

LINUS HAMMAR

Environmental Systems Analysis
Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2011

Dear BoA:
Thanks for all kind support
over the yers - now I am
halfways! Linus

THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Towards Technology Assessment of Ocean Energy
in a Developing Country Context

LINUS HAMMAR

Environmental Systems Analysis
Department of Energy and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2011

“It’s a learning process”
Sverker Molander (2009, 2010, 2011)

Towards Technology Assessment of Ocean Energy in a Developing Country Context

LINUS HAMMAR

© LINUS HAMMAR, 2011.

ESa report no 2011:13

ISSN: 1404-8167

Environmental Systems Analysis
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Gothenburg,
Sweden

Telephone + 46 (0)31-772 1000

Cover: The Indian Ocean meeting two Tanzanian generations

Chalmers Reproservice

Gothenburg, Sweden 2011

ABSTRACT

New technologies for the extraction of valuable ocean resources are emerging: renewable ocean energy. Ocean energy technologies have so far primarily been developed in industrialised countries but will be deployed in both industrialised and developing countries. Ocean energy technologies promise benefits to people and the global environment on the one hand, and carry risks to marine ecosystems on the other. Simultaneously, the world's oceans are under severe pressure from human activities, mainly due to a history of high technical development in combination with low regulation. Much could be gained by proactively examining both benefits and hazards at early stages of development. In this thesis, the Technology Assessment framework has been used to outline prerequisites for, benefits from, and adverse consequences of ocean energy technologies in developing countries. The case-study is the Western Indian Ocean (eastern Africa), a region experiencing increasing energy demand, both in fossil fuel-dependent small islands and in mainland countries with very low rural electrification levels and diesel-fuelled off-grid systems. This thesis combines technical, social, and environmental aspects. Firstly, resource overviews were performed, indicating that potentially useful ocean energy sources exist in the region. Wave power resources are abundant in southern parts of the case-study region and conditions are good for ocean thermal energy conversion (OTEC) at several locations. Secondly, the socio-technical prerequisites for the use of ocean energy technologies were examined, considering both small-scale (off-grid) and large-scale (main-grid) applications. Numerous barriers to small-scale use were identified; these should be addressed both by adapting technology and by improving institutional quality. Thirdly, the benefits of different ocean energy technologies were discussed based on the regional context of local demand and existing power systems. In rural areas, electricity demand is low and introduced power sources for off-grid electrification need to be used for productive purposes and should be accompanied by other rural development services, if economic development is to be improved. Connected to main-grids, ocean energy can provide significant amounts of fuel-independent electricity, of particular value to the small island states. Finally, environmental consequences were examined, concluding that very little is yet known. The outcomes of this thesis indicate that large-scale developments of wave power and OTEC can become important contributors to small island states in the Western Indian Ocean, while implementation of small-scale ocean energy in the region would encounter many socio-technical challenges. Due to its higher robustness, higher power output, and by-product of desalinated water, OTEC may provide the highest benefits of the two. In both cases, uncertainties regarding ecological risks remain important constraints to thorough assessment. Mitigation of ecological risks requires more research, emphasis on key ecological processes and cumulative effects in risk assessments, and efficient monitoring of impacts. At the resource-level, risks can be reduced by having a wide range of technical options to choose from (many different technologies for extracting the same resource), and by using technologies that can be further adapted, even after they have become widely used. From this perspective, wave power is the more promising ocean energy technology for the region. The thesis provides a first step towards a policy-supporting proactive Technology Assessment of ocean energy in a developing country context.

This thesis is a part of the research umbrella Socio-Technical-Ecological Evaluation of Potential Renewable Energy Sources (STEEP-RES), which focuses on evaluations of renewable energy sources (hydro, solar, wind, ocean) with the aim of enhancing sustainable energy supply in developing countries. This thesis centres on proactive analyses of the use of new resources. Other projects under the umbrella focus on how modern energy meets the needs of people, and how small-scale energy systems can be adapted in order to maximize benefits in a developing country context. STEEP-RES is a multidisciplinary umbrella where knowledge from technical, social, and natural sciences are intertwined. Participating institutions are Chalmers University of Technology, Gothenburg University, University of Dar es Salaam, and Universidade Eduardo Mondlane.

List of Appended Papers

Paper I

Hammar L., Ehnberg J., Mavumbe A., Cuamba B.C., and Molander S.
Renewable Ocean Energy in the Western Indian Ocean
 Submitted to Renewable & Sustainable Energy Reviews

Paper II

Hammar L., Ehnberg J., Mavumbe A., Fransisco F., and Molander S.
Site-Screening Method for Micro Tidal Current Turbines and a Case Study in Mozambique
 Submitted to Renewable Energy

Paper III

Hammar L., Ehnberg J., Gullström M., and Molander S.
Ocean energy in combination with land-based renewable energy sources: appropriate technology for smaller electricity grids in Africa?
 Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 2009

Paper IV

Ahlborg H., and Hammar L.
Drivers and barriers to rural electrification in Tanzania and Mozambique – grid extension, off-grid, and renewable energy sources
 Proceedings of the World Renewable Energy Congress, Policy Issues, Linköping, Sweden, 2011

Paper V

Hammar L., Ahlborg H., and Molander S.
Power Sector Actors' Views on Productive Use, Private Sector Involvement, and Renewable Energy in Rural Electrification of Mozambique and Tanzania
 Manuscript

Paper VI

Hammar L., and Gullström M.
Applying Ecological Risk Assessment Methodology for Outlining Ecosystem Effects of Ocean Energy Technologies
 Proceedings of the 9th European Wave and Tidal Energy Conference, Southampton, UK, 2011

Table of Contents

1. Introduction	7
2. Background	12
2.1. Benefits of access to electricity	12
2.2. Power sector and electrification strategies	13
2.3. Renewable energy in developing countries	14
2.3.1. Ocean energy in the developing country context.....	15
2.4. Previous assessments of ocean energy in developing countries.....	16
3. Technology Assessment.....	18
3.1 History and trends in TA	19
3.2. Applied TA procedure	21
4. Appended Papers and specific methods used.....	24
4.1. Paper I and II: physical prerequisites	24
4.2. Paper III, IV and V: socio-technical prerequisites and benefits	24
4.3. Paper VI: adverse consequences.....	25
5. Towards TA of ocean energy in the WIO	26
5.1. System boundaries (Step 1)	26
5.1.1. Case-study region.....	26
5.1.2. Temporal boundaries.....	27
5.1.3. Limits of scope.....	28
5.2. Description of the technologies (Step 2)	28
5.2.1. Technology: Wave power	29
5.2.2. Technology: Tidal barrages	30
5.2.3. Technology: Tidal current turbines.....	31
5.2.4. Technology: Ocean thermal energy conversion (OTEC)	32
5.2.5. Technology: Ocean current power	33
5.2.6 Forecasts of technology growth	34
5.3. Prerequisites for ocean energy in the WIO region (Step 3).....	37
5.3.1. Ocean energy natural resources	37
5.3.2. Socio-technical prerequisites and barriers	40
5.4. Benefits of ocean energy to the WIO region (Step 4)	42
5.4.1. Benefits from small-scale ocean energy	42

5.4.2. Benefits from large-scale ocean energy	44
5.5. Adverse consequences of ocean energy (Step 5).....	44
6. Policy-oriented summary of results (Step 6).....	48
6.1. Small-scale ocean energy in the WIO	48
6.2. Large-scale ocean energy in the WIO	48
7. Reflections.....	51
7.1. TA framework	51
7.2. The way forward.....	52
Acknowledgements	53
References	54

1. INTRODUCTION

Through recent technological advancements a new resource from the oceans can be harnessed: renewable ocean energy. Ocean energy includes energy from waves (wave power), tides (tidal power), currents (ocean current power), thermal gradients (ocean thermal energy conversion, OTEC), and salinity gradients (salinity gradient power), which can be converted into useful, clean, electric energy (Khan and Bhuyan 2009). The energy reserve is massive and ocean energy technologies are expected to become globally widespread within the near future (Esteban and Leary *in press*, Inger *et al.* 2009). Ocean energy technologies may come to supply electricity to a wide range of locations, including energy-deficient developing countries. However, for ocean energy to be an option the natural resources must be available and socio-technical prerequisites must be met. Moreover, these new technologies will operate in sensitive environments already under human pressure. Much can be gained by proactively examining not only benefits but also prevailing prerequisites and hazards at the early stages of technical development.

Research and development

Although the basic principles of using ocean energy have been explored for almost a century, both research and development have only recently picked up speed, encouraged by rising energy costs and ambitions to mitigate climate change (Esteban and Leary *in press*, Callaghan 2006). The interest in renewable energy has increased strongly in recent years, but most attention has been given to land-based sources, such as wind power, solar power, and hydropower, which are decades ahead of ocean energy in terms of technical development. This difference is reflected in the number of scientific papers published in these areas, illustrated in Figure 1. In total 3 427 papers were found using ocean energy related search terms in the Scopus scientific database, while 27 640 papers were found when using solar power search terms and 10 742 papers were found when using wind power search terms. However, research in ocean energy technologies is increasing (by more than a factor of two per decade), as shown in Figure 2. Research into wave power and tidal power has increased the most, while OTEC research had its peak in the 1980s.

Technical development of ocean energy essentially takes place in industrialised countries (Khan and Bhuyan 2009) but both full-scale installations and pilot plants have been implemented in developing countries¹ (WEC 2010). For example, the majority of ocean energy research projects and pilot plants are commissioned in the UK, but the highest capacity of ocean energy is currently being installed South Korea (254 MW) (Esteban and Leary *in press*, Bahaj 2011) and India (Bhuyan 2008, Bryden 2010), a country intent on taking

¹ There are several ways of classifying countries with respect to development status, or wealth. In this thesis I use the terms 'developing country' and 'industrialised country'. The former category includes both the least developed countries (LDC) and the newly industrialised countries (NIC). The latter category includes countries with an industrialised economy that provides wealth, freedom and safety to its citizens. This classification, based on Kofi Annan (Press Release G/05/2000), reflects the terminology in most of the covered literature. Note that it includes countries which might otherwise be classified as 'advanced economies', such as South Korea that may share more similarities with industrialised countries than with developing countries. Differences between 'developing countries' can also be substantial. This is a limiting factor to the generalizability of the results from this study.

advantage of much of its estimated 79 GW of ocean energy resources (Bakshi 1998, Bryden 2010). Massive projections have also been announced by China, the Philippines, and Indonesia. Moreover, African countries – which have the lowest electrification levels in the world and high costs of energy – have lately been approached by ocean energy firms (EWE 2011, IHTADA 2011). Despite the apparent interest in ocean energy in developing countries, few ocean energy studies have focused on developing country contexts (Figure 2).

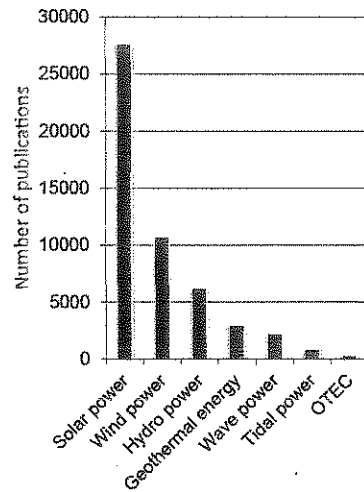


Figure 1. Number of scientific publications (research articles and reviews) on renewable energy technologies from 1962 to 2011, using the following search terms: 'wind power', 'solar power OR photovoltaic', 'hydro power OR hydropower', 'geothermal energy', 'wave power', 'tidal power', and 'ocean thermal energy conversion OR OTEC' in the Scopus database (including title, abstract, and keywords).

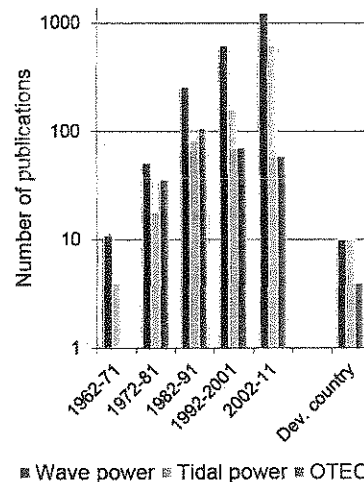


Figure 2. Number of scientific publications (research articles and reviews) on ocean energy technologies over time, using the following search terms: 'wave power', 'tidal power', and 'ocean thermal energy conversion' (OTEC) in the Scopus database. The 'Dev. Country' column shows total number of publications (1962–2011) after adding the search term 'developing countr' [countries] to each technology. Note logarithmic scale on y axis.

The main outcome of ocean energy is electricity (power) production. Different ocean energy technologies generate power of different quality in terms of intermittence and predictability. In addition, the range of power capacity varies between different technologies. These are important factors to take into account when matching technology and demand, i.e. the usefulness of a certain technology in a specific electric power system. In addition to power-related benefits to humans, ocean energy technologies may have adverse consequences to the marine environment (Frid *et al. in press*, Inger *et al.* 2009). Although some environmental effects, such as protection from fishery and enhanced local biodiversity, may be considered positive, the long-term and cumulative environmental effects caused by ocean energy technologies are difficult to predict (Inger *et al.* 2009). Importantly, adverse consequences to the marine environment are of particular concern to developing countries, where the environment often is less efficiently safeguarded compared to industrialised countries (Gamman 1994), although its ecosystem services are invaluable for local livelihood (Lange and Jiddawi 2009).

A history of unrestricted ocean exploitation

There is little doubt that the oceans are under heavy pressure from human activities (PEW 2003, MEA 2005, Halpern *et al.* 2008b). In a comprehensive synthesis of cumulative impacts, Halpern *et al.* (2008b) estimated that 41% of the oceans is strongly affected by anthropogenic environmental impacts, and that no fraction of the ocean is unaffected. The impact drivers are associated with extraction of ocean resources, pollution and waste disposal, habitat removal, changes in species composition, and climate change (Costanza *et al.* 1998, Halpern *et al.* 2008b). Coastal ecosystems are the most severely impaired (McIntyre 1992, Halpern *et al.* 2008b). Anthropogenic impacts of this magnitude to such enormous global ecosystems as the ocean would not have been possible without technical development.

The 'industrialisation of the ocean' can be traced to the European maritime activities in the 17th century, but the greatest use of technologies and intensification of activities took place with the industrial revolution in the early 19th century (Smith 2000). By then, the main activities affecting the oceans were fishery, commercial shipping, and naval undertakings. Post 1940's, the world fishery was further intensified, extraction of fossil fuels was initiated, waste disposal multiplied, and marine leisure activities were introduced. These activities, which represent the industrialisation of the oceans, have predominantly been private-sector endeavours while public-sector regulation of the ocean was very limited up to the end of the 20th century (Smith 2000). Global whale populations collapsed in the 1930s and by 2008 one third of the global fish stocks were overexploited – the most severe situation in history (FAO 2010). Weak regulation in combination with technical development – in this case trawls and seine nets, vessel and engine capacity, sonar systems, remote sensing navigation, and deep freezers – have rendered detrimental results of global scale for future generations to handle.

Fisheries provide the most evident example, but the same principles of unregulated industrial development and use of modern technology have led to multiple environmental impacts to marine ecosystems. Some different examples are oil-drilling disasters (Smith 2000), tropical shrimp farming leading to pollution and depletion of mangrove forests (Huitric *et al.* 2002), and personal water crafts (Jet Skis[®]) causing pollution, damage to environment,

and injury to large shallow-water animals (Davenport and Davenport 2006). Noteworthy is that, in addition to these discrete stressors, the oceans are strongly affected by land-based diffuse pollution such as agro-industrial fertilisers leading to eutrophication of coastal ecosystems (Diaz and Rosenberg 2008) and combustion of fossil fuels eventually contributing to, for example, coral bleaching (Hoegh-Guldberg 1999) and ocean acidification (Harvey 2008).

Time to be proactive

In our time, as technological development is rapidly changing social and ecological landscapes and spread of technology can be swift, it is often difficult to grasp the larger picture and predict consequences of emerging technologies. Most technical advances are to the immediate benefit of its users, but foresight and societal response may prevent unfortunate consequences (Rodemeyer *et al.* 2005). For this purpose, Technology Assessment (TA), which was introduced in the 1960's, has been suggested as a potent framework in need of revival (La Porte 1997, Coates 2001, Rodemeyer *et al.* 2005, Ely *et al.* 2011). TA is a framework for policy-oriented analyses aiming for better understanding of societal and environmental consequences of new technologies, with focus on unexpected and unanticipated effects (Coates 2001).

The American debate on the civil nuclear industry was the stimulus for TA, and since then many technological innovations and new technology user-areas have been analysed under the framework. Today, new technologies play an important role in the progress towards sustainable development, not least in developing countries. Ely *et al.* (2011) suggested that since technological development is often driven by powerful interests rather than by the potential beneficiaries, the policies to promote technologies that target poverty alleviation and environmental sustainability need to be informed by the best available evidence – and should be open for adaptation and improvement. In this context, TA serves to provide independent and inclusive (multidisciplinary) perspectives on the options available to decision-makers, and can be particularly valuable for developing countries (Coates 1998, Ely *et al.* 2011). In essence, TA facilitates choice of technology and technology adaptation at an early stage of development, but should not discourage technological development (Coates 1998). Importantly, both benefits and adverse consequences are considered. Regarding the ever-changing utilization of the oceans, and the potential for supplying modern energy in developing countries, the TA framework may enable early awareness of both benefits and adverse consequences of new technologies.

Objective of the thesis

On the increasing use of ocean resources, Crowder and Norse (2008) argued that "prevention is a far more robust management strategy than seeking a cure for a degraded system". At the same time, energy is vital for development and, concerning the energy situation in Africa, Bugaje (2006) concluded that "the success of sustainable development in Africa lies in addressing the imminent energy crisis in the continent" and further noted that "the only option for most African countries is the development and harness of the available renewable energy

resources". These authors did not address ocean energy specifically, but their perspectives exemplify the importance of addressing both risk and demand when studying ocean energy in developing countries. Using TA-inspired methodology and the case-study region of the Western Indian Ocean, the objective of this thesis is to contribute to a sound utilization of available ocean resources by outlining prerequisites, benefits, and adverse consequences of ocean energy technologies.

Reading guidelines

A background on electrification and renewable energy is given in section 2, ending with a review on previous assessments on ocean energy in developing countries. Section 3 provides an introduction and history on the applied framework, Technology Assessment (TA). The appended papers, which are the basis for the thesis, are presented in section 4. Section 5 and 6 presents the results and conclusions of the thesis, following the TA procedure. Finally, reflections on the methodology and the way forward are given in section 7.

2. BACKGROUND

The subsequent sections provide background to rural electrification (2.1.) and the power sector concerns (2.2.) in developing countries, and the characteristics of renewable energy sources (2.3.). It is followed by a review of available research on ocean energy assessments, with focus on developing countries (2.4.).

2.1. Benefits of access to electricity

The links between modern energy (electricity included) and development are many: health, education, gender equality, food production and conservation, improved local environment, and economic growth (UNDP 2007). This does not imply that access to electricity generates growth and social development in itself, but electricity is considered an important contributor to development. However, about 25% of the world population did not have access to electricity in the year of 2007, with sub-Saharan Africa lagging far behind other regions of the world. Rural² areas are the most disadvantaged; among the 30 Sub-Saharan African countries investigated by the World Bank (2008), less than half had rural electrification levels above 5%. The process of providing electricity to semi-urban and rural populations is a huge and expensive undertaking for any developing country – and it has taken industrialised countries 50–100 years to accomplish (Morton 2002).

Access to electricity in rural areas has been shown to generate social benefits (Gustavsson 2007a, b, WB 2008, Daka and Ballet 2011), but it has been argued that productive use³ of electricity and other rural development investments (complementary services⁴) are necessary if rural electrification is to generate economic development (Ranganathan 1993, Barnes and Floor 1996, Holland *et al.* 2001, Peters *et al.* 2009). Electricity becomes important for further progress only when a community has reached a certain level of development. In a reflection based on many years of experience from working in a non-governmental organization dealing with rural electrification, Holland *et al.* (2001) concluded that:

“Rural electrification is highly desired by rural communities, does have developmental benefits in the right circumstances (when co-ordinated with other development activities), and its expansion is a political priority.”

It should be noted that, despite general desire for electricity (which is of course regarded as a means of modernisation), electrification is not necessarily the prime priority in rural areas. Other demands, such as access to infrastructure, potable water or sanitation may be more urgent among local people (Martinot 2001). Furthermore, electricity may be a very expensive

² The definition of ‘rural’ varies between countries, and is rarely clearly stated in presented data. The American Office of Technology Assessment suggested that ‘rural’ should be interpreted as areas which are not ‘urban’ or ‘peri-urban’, generally characterized by scattered populations (Hewitt 1989). In the context of this thesis ‘rural’ refers to all areas which are not cities or towns.

³ In this thesis productive use of electricity is defined as uses that directly increase economic profit of an activity, with inflow of value to the community through increased production or refining of tradable goods.

⁴ Complementary services are services related to rural development, such as infrastructure and micro-finance institutions.

commodity, only available to the affluent part of the population. Therefore, again, it is the use of electricity and its link to other development that is important (Barnes and Floor 1996).

2.2. Power sector and electrification strategies

The power sector can be divided into three major functions: generation, transmission, and distribution. Generation means production of electricity. In developing countries, electricity is predominantly generated from sources such as hydropower, coal, or natural gas (Meyers *et al.* 1993, Schramm 1993). Transmission is necessary to transport electricity over large distance, and requires high voltage lines to minimize losses. Importantly, proximity to a transmission line does not necessarily imply access to electricity since sub-stations, where high voltage power is transformed into low voltage, are very expensive. Distribution is the part of the electric system that delivers power to customers – that is, households and other facilities – and is composed of a grid of low voltage lines (see Figure 3).

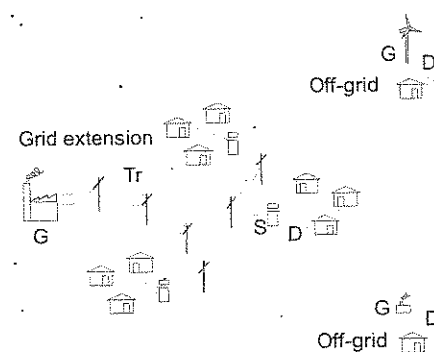


Figure 3. Conceptual illustration of rural electrification based on grid extension and off-grid systems, where G is generation plant; Tr is transmission line; S is sub-station; and D is distribution grid.

Urban electrification, as well as most rural electrification, is carried out through grid extension. However, rural electrification may also be carried out by installing small decentralized grids with their own generation sources (off-grid electrification) (Kaundinya *et al.* 2009). Off-grid systems are typically used in remote areas and on islands, where transmission is too costly an option. Diesel generators and hydropower are common generation sources in off-grid systems. The importance of off-grid systems has lately been increasingly recognized as a mean of improved poverty alleviation (because it reaches remote communities) (WB 2008). A different type of rural electrification that is becoming increasingly common is the use of solar home systems (providing low voltage direct current for domestic use) (Jacobson 2007).

It is worth noting that many industrialised countries that have undertaken electrification during the past century developed their main grids through a bottom-up procedure; by off-grid systems reaching out from rural as well as urban industrial centres, which were eventually interconnected. A similar approach led to the successful electrification of the Brazilian Amazon (Gómez and Silveira 2010).

The build-up of electricity infrastructure has traditionally been regarded as the responsibility of the public sector (Wamukonya 2003). However, energy sector reforms, undertaken by many developing countries (Karekezi and Kimani 2002, 2004, WB 2008). These reforms have included market liberalisation and commercialisation of public utilities, to attract the private sector to participate (Wamukonya 2003, Weissner 2004). Regardless of reforms, donor sponsoring and international lending play a crucial role in the financing of electrification in developing countries.

2.3. Renewable energy in developing countries

Renewable energy refers to energy sources that originate from resources that are naturally replenished within a short time perspective. Modern renewable energy sources for electricity production are, for example, small-scale hydropower (but not large-scale hydropower), geothermal electricity, wind power, solar photovoltaic and thermal electricity, and ocean energy (Johansson *et al.* 2004).

Modern renewable energy provides great opportunities for developing countries as the resources often are readily available over large areas (Painuly 2001, Weissner 2004, Bugaje 2006, Brew-Hammond and Kemansur 2009). Once the renewable energy technology is installed, the running costs can be restricted to maintenance (Williams and Simpson 2009). However, renewable energy may also incur disadvantages. In contrast to conventional fossil-fuel-based generation (e.g. coal and diesel generators) the power output of some renewable energy technologies is intermittent and unpredictable (Sahel-Koussa *et al.* 2009). Conventional generation can add fuel on demand, as long as coal/diesel/gas is available, but insulation and wind are not possible to control. Therefore, the power quality (intermittence and predictability) can become an issue for some renewable energy technologies; however, it is an issue that can be solved (Sovacool 2009, Ehnberg 2007, Babos *et al.* 2011). If intermittence is high, the generated electricity may not match the electrical loads (the use of electricity). Possible implications include interrupted activities, damaged equipment, and waste of electricity. If predictability is high, however, controllable loads can be adjusted to match power output. For example, solar power is intermittent but has a high predictability in areas with low cloudiness because daylight hours are known; wind power is also intermittent but has a lower predictability because wind speed is very variable. Where energy storage is absent or insufficient, load-based control systems are preferable (Ehnberg 2007). Load-based control systems imply that instead of adjusting the power generation to the existing loads, the loads are adjusted to what power that is available at the moment. Examples of quite easily controllable loads in rural areas are, for example, water pumping and irrigation (can also be stochastic loads, meaning that they are known to size but not in time (Blenow 2004). To control stochastic loads and adjust to intermittent power sources may incur economic losses, may still be an option.

However, the conventional way of solving the problem of intermittency is to improve power quality in off-grid by use of energy storage devices (e.g. batteries or water tanks) or by interconnecting multiple sources (Kanase-Patil *et al.* 2010). In large electrical grids, the

intermittence of renewable energy is counterbalanced by other energy sources (e.g. fossil fuel or large-scale hydropower).

Some renewable energy technologies are scalable in size (power capacity). Solar photovoltaic (PV) panels are made up of very small modules that allow the construction of small units for household-level use. Such solar home systems (<50W) have become widely available in rural markets in, for example, Kenya (Jacobson 2007). Larger solar PV systems can be used in off-grid electrification of offices, schools, or hospitals. Hydropower is also very scalable and can be used from pico-hydropower (5 kW) upwards (Williams and Simpson 2009). Even though large generators are often more efficient, small-scale applications can be very useful. For example, studies from Rwanda and Kenya report highly successful and inexpensive off-grid electrification schemes based on micro- and pico-hydropower (Maher *et al.* 2003, Pigati and van der Plas 2009). An important advantage of small systems in rural areas is the reduced capital costs (initial investment).

Renewable energy technologies used in rural electrification in developing countries incur important benefits to health and the local environment by reducing indoor air pollution, reducing the workload of women and children, and decreasing the unsustainable use of fuel wood and consequent deforestation (IPCC 2007). Other advantages of renewable energy are energy security and diversity (Weissner 2004). When electricity is produced from locally available sources, dependence on expensive and complicated fuel imports is reduced. Using a variety of energy sources, power systems become less susceptible to unpredictable situations such as droughts (hydropower), increased oil prices (diesel generators), or energy related conflicts (energy import).

From a global perspective, renewable energy technologies are regarded as important to mitigate climate change. They are not free of emissions since production, installation, maintenance, and disposal carry effluents – but life-cycle assessments of renewable energy technologies show that emissions (carbon dioxide, nitrogen oxides, sulphur oxides, and solid waste) are very low in comparison to fossil-fuel-based systems (Góralczyk 2003, Varun *et al.* 2009).

2.3.1. Ocean energy in the developing country context

When putting ocean energy into the perspective of what has been discussed in the previous sections (2.1–2.3.) it can be concluded that for ocean energy to be useful and provide benefits in a developing country context, the technologies must not only be available but also meet technical and demand-related prerequisites. The great variety of emerging ocean energy technologies comprises a wide range of (i) power capacity, (ii) power quality, and (iii) technical simplicity/complexity. Thus, different ocean energy technologies can be suitable for different power systems – from micro-scale off-grid systems to large-scale main grid supply.

2.4. Previous assessments of ocean energy in developing countries

The technical development of ocean energy technologies is available through numerous 'technology up-date' reports (Gorlov 2001, Fraenkel 2002, Ferro 2006, Block 2007, Khan and Bhuyan 2009, Khan *et al.* 2009, Rourke *et al.* 2010). According to this literature, the most promising ocean energy technologies are wave power, tidal power (both tidal barrages and tidal current turbines), and OTEC. Some attention is given to ocean current power, and least attention is given to power generation from salinity gradients. In this 'technology-update' literature, European, North American and East Asian waters are in focus.

Neither the global theoretical resource of ocean energy nor the technically extractable resource are fully known. For example, the global theoretical wave power resource has been estimated to be 8 000–80 000 TWh per year (Bhuyan 2008). However, a large number of local and regional assessments of the potential for different ocean energy technologies have been produced, some of them addressing developing countries. The first regional assessment was performed by UNEP (1983) and addressed West Africa. This study identified good potential for OTEC throughout the region, and adequate tidal power resources at a few locations. Li *et al.* (2010) concluded that China has excellent tidal current resources, that match well with the country's demand for renewable energy. This result was supported by Wang *et al.* (2011) who further argued that China has good potential for virtually all other ocean energy resources. Lim and Koh (2010) noted a promising potential for tidal current turbines in Malaysia. Zabihian and Fung (2011) reported good potential for using tidal power (tidal barrages), wave power, OTEC, and salinity gradients in Iranian waters. Several global-level assessments of OTEC resources are available, indicating good potential in a multitude of developing countries (Griekspoor 1981, Charlier and Justus 1993, Lennard 2007, Magesh 2010); detailed studies have addressed, for example, the Philippines (Uehara *et al.* 1988) and the South Pacific (Mario 2001). The generic potential for ocean energy to become established in developing countries is briefly discussed by Doukas *et al.* (2009). It is concluded that ocean energies can make an important contribution to the energy supply once the technologies are fully developed and developing country energy markets are stable.

No comprehensive ocean energy resource assessments have been conducted in the Western Indian Ocean (the case study region of this thesis). However, both wave power and OTEC are planned at Réunion Island (Drouineau *et al.* 2011), and one study has addressed the tidal power potential at a location in Tanzania (Dubi 2006).

Many of the technology updates and resource assessments include natural resources, power system requirements, economic viability, required economic support mechanisms, and notes on environmental impacts – all valuable input to TA. In addition, the very important issue of environmental impacts is also, and more thoroughly, addressed by the growing literature on environmental impacts of ocean energy (Frid *et al. in press*, Abbasi and Abbasi 2000, Inger *et al.* 2009, Langhamer *et al.* 2010). However, since ocean energy is recent, and few plants have been deployed, there are very few quantitative results available (Lamadrid-Rose and Boehlert 1988, Langhamer *et al.* 2009, Langhamer 2010). Once more quantitative results become available, it will be necessary to extrapolate data from single installations to large ocean energy farms. Further, it may be relevant to consider seascape-level impacts from ocean

energy farms co-occurring with impacts from other human activities. To assess such cumulative environmental impacts – whether from ocean energy or other technologies – is difficult. Although research studies within the field of cumulative effects assessment have addressed the problem (Therivel and Ross 2007, Halpern *et al.* 2008a), it is not evident how to proceed, as was indicated by Wilhelmsson *et al.* (2010) on the impacts from offshore wind power.

The reviewed literature contains much up-to-date information of relevance for TA of these emerging ocean energy technologies. However, in recent years the TA approach has been applied to only one study of wave power in North Carolina, USA (Hagerman *et al.* 1989). Resources, costs, performance, and ecological impacts were considered in this study, with the conclusion that: "wave energy can supply significant amounts of electricity to North Carolina without disruption of natural environmental processes, other uses of coastal sea space, or the scenic beauty of the coastline".

No TAs of ocean energy with focus on developing countries have been found.

3. TECHNOLOGY ASSESSMENT

It is understood that there is significant interdependence between society and environment, hence assessments related to components of society, technology, or environment benefit from taking a holistic approach – which means to consider the component under assessment as a part of a larger system (Olsson and Sjöstedt 2004). Assessments are, in one or another way, the basis for decisions. In this thesis, the decision regards control of technology – either through regulation, promotion, or adaptation. Decisions often imply weighing of different criteria. In this case, the most obvious criteria are related to social and environmental benefits on the one hand, and risk of adverse consequences on the other. Important characteristics that influence the appropriateness of the assessment method used for decision-support are: the type of question, the level of uncertainty, the spatial and temporal boundaries, the specific cultural context, and the need of weighing between perspectives (Wrisberg *et al.* 2002, Moberg 2006). Moreover, stakeholder participation and inclusion is important to gain public acceptance of a decision (Moberg 2006, Ely *et al.* 2011).

A major fragility of ocean energy technology assessments in developing countries is that there is no clear decision-requiring situation; the problem – how different ocean energy technologies should be treated if/when they become widely available – is still largely a hypothetical problem. However, TA is a method particularly developed for assessing emerging technologies when problems are not yet evident but “trial-and-error” is considered too risky an option (Ely *et al.* 2011).

TA methodology accounts for both benefits and adverse consequences, with emphasis on the unexpected effects (Coates 2001). Although handling of uncertainties is the traditional core of TA it does not necessarily mean that uncertainties are reduced by using TA – but that decision-makers at least are aware of them (Collingridge 1981). The spatial and particularly the temporal boundaries in a TA can be extensive, such as the long-term societal effects that are the focus of traditional TAs (van den Ende *et al.* 1998, Ely *et al.* 2011). Regarding the importance of cultural context, Coates and Coates (2003) argued that TA is not fully convertible between cultures as it is at odds with fatalistic world views. Despite this potential difficulty, TA has repeatedly been suggested as particularly suitable for developing countries (Châtel 1979, Chen 1979, Coates 1998, Ely *et al.* 2011). Weighing between perspectives – economic, social, and environmental – should ultimately be done at a policy level (La Porte 1997). However, TA should provide an interdisciplinary well-founded basis to the decision-making process (La Porte 1997, Ely *et al.* 2011). Regarding participation, the involvement of different stakeholders in the TA process has shifted back and forth over the years, but it is now accepted that TA must involve both participatory and expert-driven elements (Rodemeyer *et al.* 2005, Ely *et al.* 2011).

As TA has been chosen as a suitable assessment framework for this study, a description of its history and trends is given below, followed by the applied TA procedure.

3.1 History and trends in TA

The TA framework emerged in the 1960's and reached a prestigious status within the Office of Technology Assessment (OTA), which was created by the American Congress in 1972 with the purpose of producing an early warning system of adverse consequences of new technologies. TA was defined as “a policy study designed to better understand the consequences across the society of the extension of the existing technology or the introduction of a new technology with emphasis on the effects that would normally be unplanned or unanticipated” (Coates 2001). Consequently, TA served as a procedure for policy makers to obtain adequate and independent information concerning which societal (and later environmental) consequences new innovations or trends in research could bring about. It was recognised that technical development is fast, and that technology is closely intertwined with society. Therefore, forward-looking systemic thinking should be applied (Bhatnagar and Jancy 2003, Hellström 2003).

The OTA produced a total of 750 policy oriented reports on topics related to new technologies (for example, on the effects of fertilizers and global climate change), before it was closed down in 1995 by the Congress at the time (La Porte 1997). The close-down dampened some of the original political purpose of the TA framework. Further development of TA took place mainly in Europe and has resulted in many branches of the framework. A central issue to most TAs is the Collingridge dilemma:

“Attempting to control a technology is difficult, and not rarely impossible, because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development, but by the time these consequences are apparent, control has become costly and slow.” Collingridge (1981)

Collingridge argues that there is little to gain from trying to forecast the consequences of technologies, and that the solution to upcoming adverse consequences lies in retaining the ability to change a technology even after it is fully developed and diffused (widely used). Therefore, according to Collingridge, mitigation of adverse consequences involves (i) efficient monitoring (of potential consequences) and (ii) adaptable technologies. It should be noted that Collingridge refers to societal consequences. Environmental impacts, to some extent, can be predicted on the basis of empirical scientific methodology. However, at the ecosystem level, and when cumulative impacts are involved, environmental consequences may be as unpredictable as societal consequences. Furthermore, the consequence of Collingridge's dilemma differs with scale. At long-term strategic levels, diverse and adaptable technologies provide advantage, while at project level (operational level) best-of-the-art risk assessment is necessary.

Since the birth of the TA concept, there have been developments and shifts in the focus. The original idea was to involve legislators, executives, public interest groups, and businesses in TA, although much work at OTA was expert-driven (Coates 2001). During the 1980s and 1990s, participation of the public increasingly won ground (Shitryama *et al.* 2009) as it was

found necessary to consider prevailing norms and values to enrich TA analyses (Ely *et al.* 2011).

TA was developed in an industrialized country context, and this is where it has mostly been operating since. But it has repeatedly been argued that TA is of relevance to developing countries (Châtel 1979, Chen 1979, Coates 1998, Coates and Coates 2003, Ely *et al.* 2011). This is due to some converging trends: globalization, industrialization, increased consumption and population growth, failure to anticipate side effects of unfamiliar technologies, and the expansion of multinational enterprises into developing country markets. Technical development, both in industrialized and developing countries, has frequently produced unanticipated adverse consequences, which most often are unnecessary and the result of ignorance (Coates 1998). Here, the goal of TA is to avoid such mistakes by being proactive in policy-making and to widen technological choices (but not to prevent technological development). An example of a TA institution operating in a developing country context is the Forecasting and Assessment Council (TIFAC), which works under the Government of India's Department of Science and Technology (Bhatnagar and Jancy 2003). The TA procedures of this institution have been a basis for this thesis.

Today, a great variety of TA branches are being used in different fields of research and development, policy-supporting governmental institutions, and consultancy. For example, medical TA is widely used for assessing the unexpected benefits and consequences of new drugs; participatory TA is a recent approach aiming to involve public interests in technology-related policy (Anon. 2010, Sclove 2010). TA branches of particular relevance for this thesis are Energy TA (ETA), Constructive TA (CTA), and Environmental TA (EnTA), which are briefly described below.

ETA serves as a support for energy system policy-making regarding technology requirements and performance (including both benefits and consequences). The objective may not diverge much from the original TA but there is typically a focus on economic factors (see Daim *et al.*, 2009). For example, in practice, an ETA may not differ much from a straightforward quantitative evaluation of the technical, economic, and operational characteristics of an energy system (La Porte 1997). A variety of assessment tools, including energy system modelling, can be used for estimating and weighing the benefits and impacts (Segurado *et al.* 2009). The American Energy Technology Assessment Center (ETAC) describes its research approach as "focusing on interdisciplinary analysis of technology development, energy policy, and economic factors" (EPRI 2011). Noteworthy, the Collingridge dilemma becomes particularly delicate for energy technologies since the lead time (the delay between initiation and implementation) is extraordinarily long. Strategic decisions regarding promotion of and investment in energy technologies determine which technologies are available in the energy system 30–40 years later (Collingridge 1981).

CTA was developed in the Netherlands in the 1980's and differs from other TA approaches in that it seeks to change/adapt the design and performance of a technology rather than to select between technologies or regulate use. Consequently, CTA requires a higher and more direct involvement of developers (van den Ende *et al.* 1998, Rodemeyer *et al.* 2005). Social aspects have a major role in CTAs, and technology developers contribute from the start by adapting their products in the desired direction in parallel to the assessment process, thereby

seeking to socially assimilate the technology. Environmental impacts may be incorporated as a factor of social acceptance, but are often not specifically considered.

EnTA has been developed and promoted by UNEP's Division of Technology, Industry and Economics (Hay and Noonan 2000). EnTA focuses on environmental impacts, although it also emphasizes benefits, and it was developed with particular focus on developing-country applications (Coates 1998). The EnTA framework is qualitative, conducted by multidisciplinary expert groups who, through structured evaluations, advise whether and, if so, how new technologies should be encouraged. It has been argued that since EnTA specifically addresses developing countries it should be better adapted to the developing country context (Coates and Coates 2003, Tran 2007). Despite its apparent relevance, the EnTA framework has not become widely used.

Returning to the choice of assessment method for this thesis, some aspects motivating the use of the TA as a suitable framework can be added to what was previously discussed: the novelty and diversity⁵ of the technologies (choices and adaptations are open), the particularly little attention paid to developing countries in previous ocean energy research in combination with high uncertainty regarding adverse consequences (potential problems are unanticipated), and the critical state of the oceans including sensitive tropical ecosystems (need for proactive analyses).

All three sub-divisions of TA discussed above may be of relevance to understanding the full impacts of ocean energy to humans and the ecosystem. ETA supports the use of technical and economic assessments, the diversity of technologies motivate CTA approaches with dialogues between assessors and developers, and the ambitions of EnTA, including focus on environment and developing countries are essential to assessments of ocean energy.

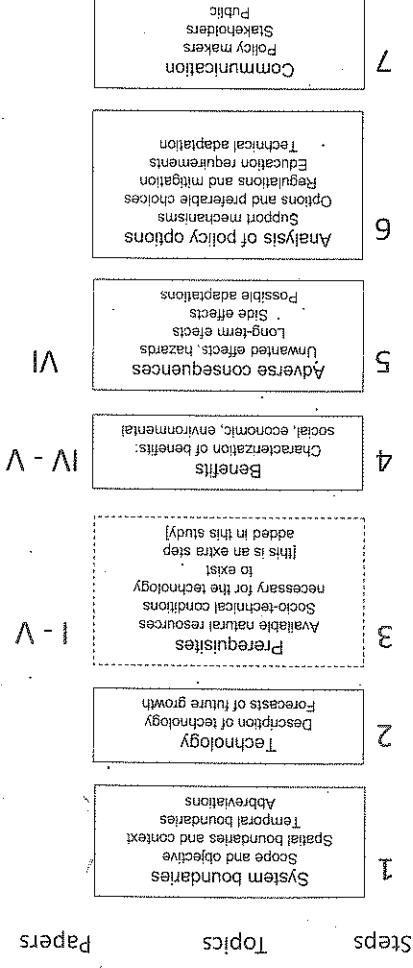
3.2. Applied TA procedure.

The TA procedure used in this thesis was modified from schemes presented by Bhatnagar and Jancy (2003) and the Institute of Technology Assessment in Vienna (ITA 2011) (Figure 4).

The first step of the procedure is the definition of system boundaries. Scope and objective define which technologies are under study, and in which context. It is obviously of fundamental importance to the outcome (Bhatnagar and Jancy 2003). To set the spatial boundaries is important to any assessment and can, in brief, vary between local, regional, and global (Wrisberg *et al.* 2002). Regarding temporal boundaries, strategic decisions – which characterize TA – are based on scenarios. Scenarios can be classified as being *predictive*, addressing 'what will happen?' given a particular prevailing structure; *explorative*, addressing 'what can [possibly] happen?' given a particular future change; or *normative*, addressing 'how can a specific (far-future) target be met?' (Börjeson *et al.* 2006). Extensive time horizons increases uncertainties, but short time horizons may be insufficient for revealing important findings (Bhatnagar and Jancy 2003).

⁵ Khan and Bhuyan (2009) have identified >130 technically different ocean energy devices.

Figure 4. The TA procedure used, modified from (Bhatnagar and Jancy 2003, ITA 2011). This diagram also indicates where the main contributions from the appended Papers I-VI fit into the procedure. The dashed box indicates the modification for this case-study. Note that this thesis has focused on Steps 3-5.



The second step includes technical description of the technologies under scrutiny, technology forecasting and description of the studied technologies in relation to its alternatives.

The third step, 'prerequisites', is a modification done specifically for this thesis. It includes the natural resources and socio-technical aspects of the case-study region. The prerequisites could also be regarded as part of the 'scope' or of 'forecasting of growth' (Bhatnagar and Jancy 2003). This slight modification was done because of the context of this case-study: both energy resources and human demand and capacity need to be addressed explicitly. Prerequisites related to natural resources are persistent (although technology can develop so that the resources can be more efficiently utilized). Socio-technical prerequisites are likely to

change over time with societal development and may alternatively be regarded as barriers that can be affected (diminished) by actions.

The fourth step includes a characterization of the benefits of the technologies. Benefits can be related to, for example, economy, health, environment (local or global), social development and comfort. It should be clear which benefits the technologies has in relation to the alternatives (Bhatnagar and Jancy 2003, ITA 2011).

The fifth step, adverse consequences, involves the identification of unwanted effects or hazards that the technologies may pose or induce to health, environment, or society. Long-term effects and side-effects (*i.e.* less obvious, secondary, effects) should be in focus (Coates 2001, Bhatnagar and Jancy 2003, Rodemeyer *et al.* 2005, ITA 2011). In this step possible mitigation measures or technical adaptations may be revealed.

The sixth step is the outcomes, which should describe and possibly weigh the benefits and consequences in order to generate policy recommendations regarding support mechanisms needed, suitable regulations or mitigation measures, education requirements, preferable choices among available alternatives, and preferable technical adaptations (Bhatnagar and Jancy 2003, ITA 2011). This step has only been briefly approached in this thesis, as the extent of the studies is limited.

Finally, the seventh step is the communication of outcomes, not only to policy makers but also to other stakeholders, including the public (this step is outside the scope of this thesis).

Although the TA procedure is depicted as linear, the work, by necessity, implies iterative analyses with feedback loops between the steps. One example is 'forecasts of technology growth' which is included in Step two, is also a necessary input when setting the temporal boundaries in Step one. This is a typical detail capturing the difficulties in transferring complex analytical processes into conceptual models, which has previously been recognised by Miser and Quade (1988).

This thesis is laying ground for more thorough and participatory assessments, but it is not a TA in itself. Because of this, there has been limited emphasis on the last two steps (Analysis of policy options and Communication). Although some pertinent results are outlined, the delicate task of weighing between benefits and risk has not been undertaken in this thesis.

4. APPENDED PAPERS AND SPECIFIC METHODS USED

This section gives a brief introduction the appended Papers I-IV.

4.1. Paper I and II: physical prerequisites

Two studies have addressed the physical prerequisites (natural resource abundance) of ocean energy in the case-study region. Paper I investigates the natural-resource-based potential of each ocean energy technology. The assessment was based on a meta-analysis of information collected from the literature and databases. For wave power, data was extracted from global resource assessments (Quayle and Changery 1981, Barstow *et al.* 2008) and analysed without any recalculations. The potential for land-based OTEC was estimated through spatial analysis (ArcGIS software) of oceanographic data available in the African Marine Atlas (Masalu *et al.* 2006). Tidal power potential was estimated by collecting information on tidal elevations from local tidal charts and tidal gauge data-bases, and by extracting information on maximum current speeds at different locations from published reports and scientific papers. The tidal data was used to estimate power output by applying simplified tidal models and equations for power generation (Gorlov 2001, Fraenkel 2002). Furthermore, oceanographic literature and historical ship data (Cutler and Swallow 1984) were compiled to examine the potential for ocean current power.

In Paper II, the resource-based prerequisites for micro-scale tidal current turbines were investigated through field measurements at five locations in Mozambique. Here, micro-scale refers to tidal power devices with capacities in the order of 20 kW, which may be useful for off-grid electrification in remote areas. The main objective of the study was to develop a cost-efficient method for site-screening, since full-time measurements were considered too costly for a micro-scale approach. The applied model was based on an existing equation for tidal currents (Fraenkel 2002) and the collected short-term observations were used for site-specific calibrations. Technical assumptions for a hypothetical micro tidal current turbine were used to exemplify power output. The estimated output was discussed in terms of energy demand in rural developing communities.

4.2. Paper III, IV and V: socio-technical prerequisites and benefits

Paper III discusses the socio-technical preconditions for using small-scale ocean energy for rural electrification purposes. It assumes the possibility of an ocean energy market niche in remote areas of developing countries, where small-scale energy sources are needed to substitute fuel-dependent diesel generators. Based on a literature review, the study outlines challenges regarding the use of appropriate technology in the context of remote area electrification and discusses how the different ocean energy technologies could be adapted.

In Papers IV and V, interviews were carried out in Tanzania and Mozambique, to investigate how actors at the policy-making and project-leading levels perceive and reflect upon rural electrification strategies, their own contributions, and the opportunities to increase the use of renewable energy sources. The interviews were qualitative (non-empirical) and

semi-structured, which means that the interviews followed a predefined scheme of topics and questions, but were not strict in the phrasing of questions. The interviews were recorded, transcribed, and analysed using the Content Analysis procedure described in Mikkelsen (2005). Paper IV specifically examines the perceived drivers and barriers to rural electrification, while Paper V focuses on actors' reflections on productive electricity use, private sector involvement in the electricity sector, and the opportunities for using renewable energy sources for off-grid electrification. Both studies aim to provide a deeper understanding of energy demand and the potential for different energy sources and strategies in rural areas of developing countries.

4.3. Paper VI: adverse consequences

Paper VI provides a hazard identification of potential adverse environmental impacts of ocean energy technology to marine ecosystems. The hazard identification, followed by a qualitative risk-ranking, was conducted by review of scientific papers describing potential environmental impacts from wave power, tidal current turbines and OTEC. While the result reflects the current state of scientific knowledge, the deeper purpose of the study was to test the Ecological Risk Assessment (EcoRA) framework (Suter and Barnthouse 1993) in the context of ecosystem-based management – a concept that has gained recent attention but is still unclear in terms of practical implementation. The EcoRA procedure is structured around stressor sources, exposure pathways and endpoints. The main steps of the procedure: scope (including the definition of system boundaries and assessment endpoints), hazard identification (inventory of relevant stressors), exposure assessment (establishment of pathways and characterization of the probability of stressors reaching the endpoints), effect assessment (estimating the magnitude of effects on the endpoints), risk characterization (the product of the previous two steps), and risk evaluation (the basis for decision-making) (Suter and Barnthouse 1993, Burgman 2005). Paper VI does not focus on the developing country context in particular.

5. TOWARDS TA OF OCEAN ENERGY IN THE WIO

This section presents the basic assumptions and the results of conducted studies, presented in accordance with the applied TA procedure. It begins with defining the system boundaries (5.1) and description of technologies including forecasts of future growth (5.2). The results from appended Papers are then used to outline prerequisites (5.3), benefits (5.4), and adverse consequences (5.5) of ocean energy in the WIO.

5.1. System boundaries (Step 1)

The system boundaries include a description of the geographical extent and context of the case-study region (5.1.1), the temporal boundaries (5.1.2), and the limits of scope (5.1.3).

5.1.1. Case-study region

This study has a regional approach, applying the Western Indian Ocean (WIO) as the case-study (Figure 5). The WIO, defined in Spalding *et al.* (2007), includes the coastal areas of Mauritius, and southern parts of Somalia (although Somalia has not been included in this thesis). The WIO was divided into 13 smaller regions to facilitate the analyses.

The WIO was chosen as the case-study because (i) the region is one of the most energy-deficient parts of the world and is in deep need of greater access to electricity (WB 2008); and (ii) the region includes countries with very different power sector requirements (Weisser 2004) such as small island states with small electric grid-connected populations and expensive energy imports, and African mainland countries with long coastlines, scattered populations with little access to electricity, but high abundance of other energy sources.

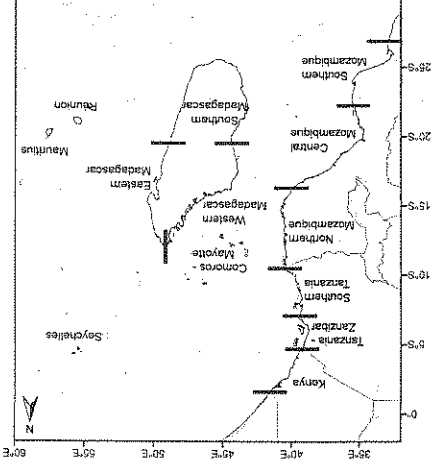


Figure 5. Map of the Western Indian Ocean region (WIO) which constitutes the case-study region of this thesis. For analysis purposes the WIO was divided into 13 smaller regions indicated by their name (borders between smaller regions are marked with black strokes).

5.1.2. Temporal boundaries

In short, the WIO region provides a developing country context where the electricity situation can be described as: small islands with high electrification levels but an expensive dependence on fossil fuel imports, and large mainland countries with low total electrification levels and extremely low rural electrification levels but available unexploited energy resources. A more detailed description of the electricity access and power generation is given in Paper I. In addition, many coastal areas suffer from freshwater shortages.

The WIO countries (Somalia excluded) have a total coastline of 10 660 000 km and the included countries (Kenya, Tanzania, Mozambique, Madagascar, Comoros, Mayotte (France), Seychelles, Réunion (France), and Mauritius) have a total population of circa 128 million (data compiled from the CIA World Factbook, 2010). On the islands, all people live in coastal areas (100 km from sea). In mainland countries, apart from Kenya, one third to a quarter of the population lives in coastal areas. With the exception of the Seychelles, Mauritius and Réunion, both population growth and urbanization are very high (Sinclair and Richmond 2002). In coastal rural areas, the livelihood of people is strongly dependent on coastal ecosystem services such as fishery (fish constitute 75% of the daily protein intake), aquaculture and mangrove forestry (Sinclair and Richmond 2002). Moreover, tourism is important in many locations. For example, Lange and Jiddawi (2009) calculated that coastal ecosystem services amount up to 30% of GDP in Zanzibar (including both rural and urban populations). Thus, the livelihood of coastal populations in the WIO is very sensitive to marine environmental degradation, whether of local or global origin.

This study can be classified as being predictive-forecast-oriented, addressing 'what will happen on the condition that the likely development unfolds' (Böjgeson *et al.* 2006). This is because the study does not only consider what could happen if ocean energy is taken into use in the case study region ('what if scenario'), but also considering the probability for this to happen – which is related to the probability of ocean energy technologies becoming widely available in the world and the prevailing prerequisites in the case-study region.

Because uncertainties tend to increase with time, the temporal boundaries for predictive forecasts are typically relatively short (Bhatnagar and Jancy 2003, Böjgeson *et al.* 2006). In this case, the temporal boundaries must be long enough to allow for technical development to proceed until ocean energy systems may become widely available (Doukas *et al.* 2009), and it must be considered that lead times for energy technologies are typically long (Collingridge 1981). The temporal boundaries were, hence, set to present-to-2050. It is believed that by 2050, ocean energy technologies will have reached several percentage points of the total global energy supply (Esteban and Leary *in press*). It is also likely that population growth and economic development in the WIO will have imposed changes to the socio-technical preconditions, which may have implications for the validity of the study. However, since the region is one of the most energy-deprived and underdeveloped in the world, it will probably still be a developing country context.

5.1.3. Scope limitations

Regarding adverse consequences, only impacts to the marine environment have been considered, which implies a reduced focus on societal consequences. This limitation of scope is not in line with the TA framework (Bhatnagar and Jancy 2003, ITA 2011), but research on this issue is currently being conducted under the same research umbrella (STEER-RES) and results may be added to future work.

The limitation to (local) impacts on the environment is motivated by the comparatively low (global) emissions from renewable energy technologies (section 2.3.) and the estimations provided by the few life-cycle assessments that are available: it has been estimated that the CO₂ emissions from wave power devices will be <50 g CO₂/kWh (Callaghan 2006, Banerjee *et al.* Unpubl.) and a large tidal current turbine emits 15 g CO₂/kWh (Cooper and Sheate 2002). These values are in the order of 2% of the CO₂ emissions released from fossil fuel-based energy systems (Cooper and Sheate 2002).

Another limitation of the thesis is that maritime legislation, related to 'sea use', has not been included in the presented studies. This issue may be of importance for more detailed country-level studies and can be expected to change within the time-frame of the study.

5.2. Description of the technologies (Step 2)

The analyses in this thesis are based on the separation between large-scale use and small-scale use of different technologies. Here, large-scale refers to ocean energy that is connected to the main electricity grid, while small-scale refers to the use of ocean energy in off-grid systems. The latter is strongly linked to rural electrification. The use of ocean energy for rural electrification has been suggested before (Anderson *et al.* 1993, Charlier 2001, Wang *et al.* 2011), but it is not a common topic in ocean energy literature.

The study considers wave power, tidal power (including traditional tidal barrages and modern tidal current turbines), OTEC, and ocean current power. It does not include salinity gradient conversion (electricity generation based on the osmotic gradient between ocean and freshwater reserves), because this technology is represented by very few active developers. Offshore wind power is also not included because it is rarely considered an ocean energy technology (Khan and Bhuyan 2009).

The five technologies included in the present assessment are described briefly below, in terms of natural resource, conversion principles, technical diversity, and quality of power output (intermittency and predictability). Further technical descriptions are given in Paper I. This coarse level of detail (five technologies) has been applied because there are many different developing prototypes/devices and uncertainties are high regarding which of them may eventually become widely available.

5.2.1. Technology: Wave power

Number of different concepts/devices: ~90

Capacity range per device: 20 kW – 1 MW

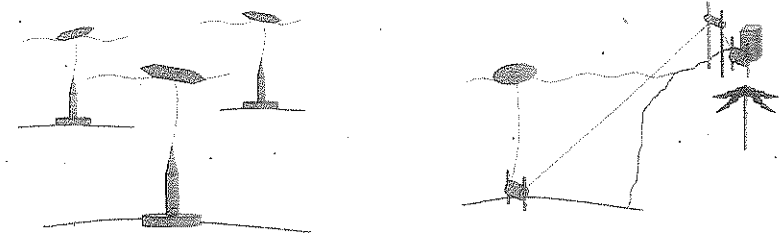


Figure 6. Conceptual illustrations of wave power devices used for large-scale deployment in farms (left), or small-scale deployment for remote-area electrification (right). The drawing indicates only two examples out of about 90 currently developing designs. The drawings are not accurate in detail or scale.

Wave power (Figure 6) uses wind-driven surface waves to generate electricity either by (i) Oscillating Water Column Systems, where waves pressurize air chambers and spin turbines, (ii) Absorber Systems, where a floater connected to the bottom is dragged up and down by the waves in order to spin turbines or drag pistons through linear generators, (iii) Overtopping Systems, where waves force water into an elevated reservoir which is emptied through low-head turbines, (iv) Inverted Pendulum Systems, where waves force a bottom-mounted oscillator to move back and forth and pressurize fluids connected to generators, or (v) other 'less common solutions' such as elongating attenuators (interconnected elongated floaters) where the wave motions pressurize hydraulics connected to internal generators (Thomas 2008, Khan and Bhuyan 2009). Wave power devices can be shore-based, mounted in shallow water, or anchored in deeper water. Floating wave power units are small but are generally intended for use in farms (Thomas 2008).

The wave power resource is measured in terms of energy density per wave crest (kW/m) (Barstow *et al.* 2008). Wave energy dissipates slowly and wind-driven waves can travel long distances and reach shores far beyond their origin. Wave power is variable and undergoes both seasonal and daily changes, but it is less variable and more predictable than wind power (Charlier and Justus 1993, Doukas *et al.* 2009). Long-distance waves (swell), which characterize tropical oceans, even out much of the short-term variation and thus, wave power around tropical islands can be particularly stable (Cornett 2008).

5.2.2. Technology: Tidal barrages

Number of different concepts/devices: few

Capacity range per device: 40 kW – 500 MW+

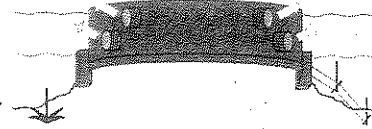


Figure 7. Conceptual illustration of a tidal barrage, large or small-scale. The drawing is not accurate in details or in scale.

Tidal barrages (Figure 7) use the incoming tidal wave (flood) to capture water inside a barrage (enclosure), which creates a head between the barrage and the natural sea level when the tide recedes during ebb. Electricity is generated when the water levels are allowed to even out through low-head turbines. Tidal barrages can operate in (i) a one-way mode where electricity is only produced during ebb, (ii) a two-way mode where electricity is generated during both flood and ebb (Charlier and Justus 1993, Charlier 2003). In addition, the barrage can be divided into different basins so that outflow can be adjusted and power output prolonged over the tidal cycle. Tidal barrages are normally constructed across natural bays or river inlets in order to minimize the length of the barrage. Modern tidal barrages may also be constructed on offshore banks (TE 2010). Tidal barrages are based on conventional hydropower technology and can be constructed both at the micro-scale (tidal ponds) and at the mega-scale (Charlier and Justus 1993, Gajanyake *et al.* 1998).

The tidal resource is dependent on the tidal range (m), that is, the local magnitude of the tidal wave, which varies between locations due to bathymetry and landmass positioning (Charlier and Justus 1993, Gorlov 2001). Further, the amount of energy extracted depends on the size of the enclosure. Tides originate from the gravitational forces between Earth, sun and moon. A tidal period is 24 h 50 min, which means that a tide rises and falls one (diurnal tides) or two (semi-diurnal tides) times per day – but not in exact phase with the period of human activities (24 h) (Gorlov 2001). Moreover, the magnitude of tides increases two times per month (spring tides), when the gravitational force of the sun adds to the force of the moon. The power output of tidal barrages is therefore variable over hours and weeks, but also highly predictable. This variation can be modified with barrage design (Prandle 1984, Hammons 1993).

5.2.3. Technology: Tidal current turbines

Number of different concepts/devices: ~40

Capacity range per device: 10 kW – 5 MW

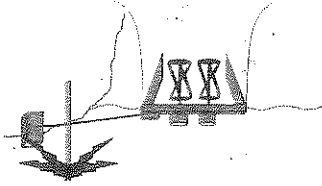
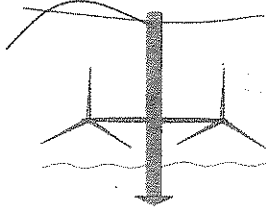


Figure 8. Conceptual illustrations of tidal current turbines, representing a large horizontal-axis turbine (left) and a small vertical-axis turbine (right). The drawings indicate only two examples out of about 40 currently developing designs. The drawings are not accurate in details or in scale.

Tidal current turbines (Figure 8) extract kinetic energy from the fast-flowing currents that develop where the tidal wave passes through narrow straits or bends around peninsulas (Kowalik 2004). Electricity is generated through turbines driven by submerged (i) horizontal rotors (like wind power), (ii) vertical rotors, (iii) oscillating hydrofoils, or (iv) other less common solutions (Khan and Bhuyan 2009, Khan *et al.* 2009). The water flow over the rotor can be enforced by mounting ducts/shrouds over the turbine (Khan *et al.* 2009). Larger tidal current turbines are installed on land, halfway or fully submerged (but always with the rotor submerged). Small turbines can be placed floating on a raft-like structure (Khan *et al.* 2008). As with wave power, tidal current turbines can be deployed in large numbers (farms) to increase the total capacity.

The tidal current resource is determined by the speed of the current (m/s), and as energy content of water is related to the cube of its speed, the resource potential increases dramatically with increasing water speed (Gorlov 2001, Fraenkel 2002). As with tidal barrages, the power output is determined by the tidal period. Every 24 h 50 m energy can be extracted during one or two flood currents and one or two ebb currents (depending on the periodicity of the tides), and two times per month currents are increased. Consequently, the power output varies over hours and weeks but is highly predictable.

5.2.4. Technology: Ocean thermal energy conversion (OTEC)

Number of different concepts/devices: **few**

Capacity range per device: **1 MW – 100 MW**

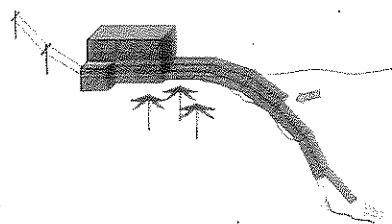


Figure 9. Conceptual illustration of land-based OTEC power plant, for large-scale production of electricity and possibly freshwater. The drawing is not accurate in details or in scale.

Ocean thermal energy conversion (Figure 9) utilizes the temperature difference between warm surface water and cold deep-sea water (Khan and Bhuyan 2009, Krock 2010, Magesh 2010). Surface water and deep-sea water are collected from the ocean via large diameter pipes and then released back to the ocean or partly utilized as freshwater. Electricity can be generated using one of three different designs; in the open-cycle design (i) warm water is vaporized in low pressure chambers and used to drive turbines before it is re-condensed by cold water; in the close-cycle design (ii) warm water heats up a working fluid that vaporizes and drives turbines before it is re-condensed by cold water and recycled in the process; in the hybrid design (iii) warm water is vaporized as in the open-cycle design and then used to vaporize a working fluid which in turn drives turbines. Freshwater production (open-cycle and hybrid design) adds value to the process, and can even be the main purpose of OTEC (Bhuyan 2008). OTEC power plants can be installed on land or floating in the deep sea. Due to the requirement of massive amounts of water, only large scale plants can become viable. By adding solar heaters to warm up the surface water the efficiency of the process can be improved (Straatman and van Sark 2008, Yamada *et al.* 2009).

The OTEC resource is determined by water temperature differences (ΔT) and its availability, which in the case of land-based OTEC is determined by the distance between shore and deep-sea water (1000 m depth is often assumed to be enough) (Griekspoor 1981, Nihous and Syed 1997). The temperature difference originates from solar heating of surface water and transport (oceanic deep-water currents) of cold water from the Poles to tropical regions. As the heating and currents are relatively constant, OTEC power production is predictable although it may vary slightly over seasons (Bhuyan 2008, Vega 2011).

5.2.5. Technology: Ocean current power

Number of different concepts/devices: **very few**

Capacity range per device: **200 kW – 3 MW+**

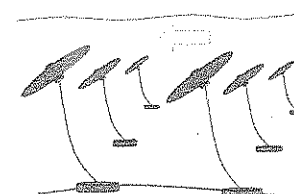


Figure 10. Conceptual illustration of ocean current power, consisting of several small units where turbines are mounted on submerged kites and used in large-scale applications (farms). The drawing is inspired by the Minesto Deep Green technological design and is not accurate in details or in scale.

Ocean current power utilizes the massive but relatively slow (compared to tidal currents) oceanic currents. Electricity is extracted using the same principles as those of tidal current turbines, but in order to get sufficient water speed over the rotors the flow can be enhanced by using different solutions (Charlier and Justus 1993). One solution is (i) to mount the turbine on an underwater kite that is fixed to the sea bed by a wire and forced in circular movements by the current (the water flow over the mounted rotor is enhanced as the kite is moving) (Minesto 2011)(Figure 10). Another solution (ii) is to apply massive shrouds/ducts over the rotor. To access the ocean currents this technology has to be deployed in relatively deep water (approx. 50–100 m or deeper). Although both small and large prototypes exist, ocean current power can only be expected to become feasible in large-scale applications (farms of many units), because of the distance to the coast and expensive transmission (Finkl and Charlier 2009).

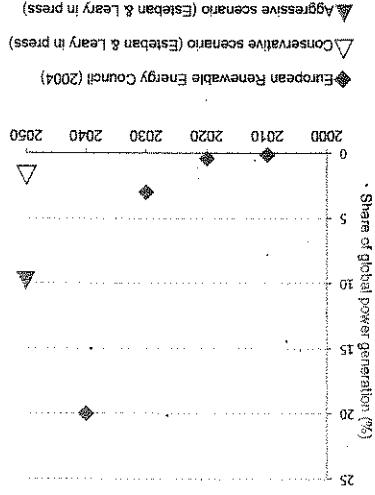
The resource is determined by the speed of the current (m/s), as for tidal current turbines. But in contrast to tidal currents, oceanic currents are invariable on a daily basis and only change over the seasons.

5.2.6 Forecasts of technology growth

Ocean energy technologies are generally still at an early stage of development, the exception being tidal barrage technology, which has been in operation for many decades and is considered a mature technology. On a theoretical technology maturity curve, wave power and tidal current turbines are considered to be at the 'pre-commercial' level, while OTEC is still at the 'testing' level (IHS 2010). Other ocean energy technologies can be considered to be at the lower 'concept' level. Since there are many different devices within each technology category, these maturity levels should be regarded as approximations.

In the past 2–3 years the number of full-scale installations (wave power, tidal barrages, tidal current turbines, and OTEC) has increased remarkably (Pillai and Banerjee 2009, Bryden 2010, Krock 2010, Bahay 2011). A substantial number of pilot-plants have also been deployed around the world, and feasibility studies for large projects are being carried out in the UK, South Korea, Australia, India, Indonesia, Réunion, and the Philippines, among others.

Figure 11. Forecasts of ocean energy contributions to the world electricity production. Both the European Renewable Energy Council (EREC 2004) and Esteban and Leary have used offshore wind power growth as the basis for their projections. The conservative and aggressive scenarios differ in their assumptions of initial growth rate. All three scenarios indicate that ocean energy will contribute significantly to global electricity generation.



At this early stage of development, reliable forecasts of technology growth are difficult to generate. Esteban and Leary (*in press*) provide the most recent projection, estimating that ocean energy will contribute with between 1.7 and 9.8% of the global energy production by 2050 (Figure 11). The more aggressive of these scenarios assumes a faster initial growth rate than the conservative scenario. An earlier projection by the European Renewable Energy Council estimated that the contribution will be of 20% by 2040 (EREC 2004). These projections are all based on the growth pattern experienced by offshore wind power, an assumption that carries many uncertainties. On the one hand, the submerged parts of many ocean energy systems require more advanced engineering than offshore wind power; on the other hand offshore wind power has been a pioneer and much can be learnt from it both

technically and regarding required financial support mechanisms. The latter argument is emphasized by Bahay (2011) and suggests that the assumptions of a growth rate similar to offshore wind power is likely to be an understatement for ocean energy. Costs of energy (US\$ per kWh) and capital costs (investment cost) are the prime economic factors for determining which of the available energy sources are most suitable in particular situations (Qurashi and Hussain 2005). The capital cost is of particular importance to many developing countries due to limited access to investment capital. Qurashi and Hussain (2005) used cost estimations from UNDP (2007) to compare the potential of different renewable energy sources. The predicted capital costs of wave power, tidal power, OTEC, and ocean current power (US\$ 1500–3000 per kW) were lower than for solar PV (US\$ 5000–10 000 per kW) and solar thermal electricity (US\$ 3000–4000 per kW), but higher than for other renewable energy technologies (US\$ 900–3000 per kW); all very approximate values (Qurashi and Hussain 2005).

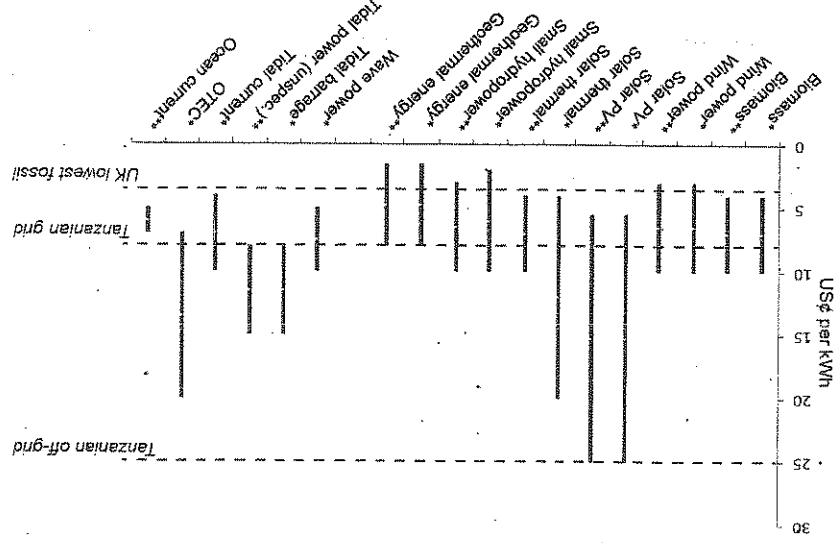


Figure 12. Predicted future cost of energy for electricity-producing renewable energy sources (vertical bars) and costs/levels for conventional electricity production (horizontal lines); lowest fossil-based electricity in UK (Callaghan 2006); Tanzanian grid-connected electricity sale tariff (EWURA 2011a); and Tanzanian off-grid feed-in sale tariff for small producers (EWURA 2011a), respectively. Note that fossil-based costs represent current costs while presented renewable energy costs are forecasts from 2000–2005. Renewable energy cost estimations acquired from: *Turkmenburg, W. Utrecht University, The Netherlands. Unpublished. (Johansson *et al.* 2004); **World Energy Assessment 2000. Energy and Challenge of Sustainability. UNDP report. (Qurashi and Hussain 2005)

In terms of costs of energy, predictions presented in Johansson *et al.* (2004) and in Qurashi and Hussain (2005) positioned wave power and tidal current turbines close to or slightly above electricity-producing biomass and wind power, but above hydropower and geothermal energy, and below solar PV (Figure 12). Tidal barrages and OTEC were predicted to have lower costs than solar PV but higher costs than other renewable energies. Ocean current power was predicted to have low costs. However, these cost estimations were conducted approximately 10 years ago and must be regarded as highly uncertain. Noteworthy is that, despite the high costs of OTEC (due to capital costs), Qurashi and Hussain (2005) suggest that OTEC will become the most preferable ocean energy technology in developing countries.

In a similar study, the International Energy Agency (IEA 2007) predicted the costs of energy for the first larger installations to be US\$ 15–55 for wave energy and US\$ 11–22 per kWh for tidal energy. Similar numbers were estimated by the Carbon Trust (Callaghan 2006). According to Callaghan (2006), although high, the costs of wave and tidal power can be expected to reach fully competitive levels relative to fossil fuels within the near future. The lowest fossil fuel-based electricity cost in 2006 was US\$ 4.5 in United Kingdom (Callaghan 2006). More detailed, Esteban and Leary (*in press*) estimated that both wave power and tidal current turbines may become economically competitive compared to oil by 2017–2021. These calculations were based on the same production cost assumptions and feed-in tariffs (standard contract for renewable energy electricity sold to a utility) as are currently being used in Portugal: US\$ ~30. Tariffs can be high (and beneficial for renewable energy) both because of political ambitions to promote renewable energy (as in Portugal) and because of exaggerated oil prices in remote locations. For example, in Tanzania the established feed-in tariff for off-grid renewable electricity is US\$ ~25 (EWURA 2011b), because costs are based on expensive diesel alternatives.

Furthermore, Clean Development Mechanism (CDM) is expected to play an important role for large-scale renewable energy implementation in developing countries, and thus can become important for ocean energy growth (Doukas *et al.* 2009). CDM is an international agreement outcome of the Kyoto Protocol (2005) that intends to counterbalance the net carbon dioxide emissions from industrialized countries by allowing them to trade emission-reducing investments in developing countries. As the first ocean energy CDM-project a South Korean tidal barrage of 254 MW was registered at the CDM Executive Board in 2006 and is now operating (UNFCCC 2011).

Based on the presented growth forecasts, it can be considered likely that some of the emerging ocean energy devices will become widely available, both for industrialized and developing countries, within the time perspective used in this thesis (*i.e.* 2050).

5.3. Prerequisites for ocean energy in the WIO region (Step 3)

5.3.1. Ocean energy natural resources

For ocean energy to become useful and profitable, both physical and socio-technical prerequisites have to be satisfied. These issues have been investigated in Papers I and II.

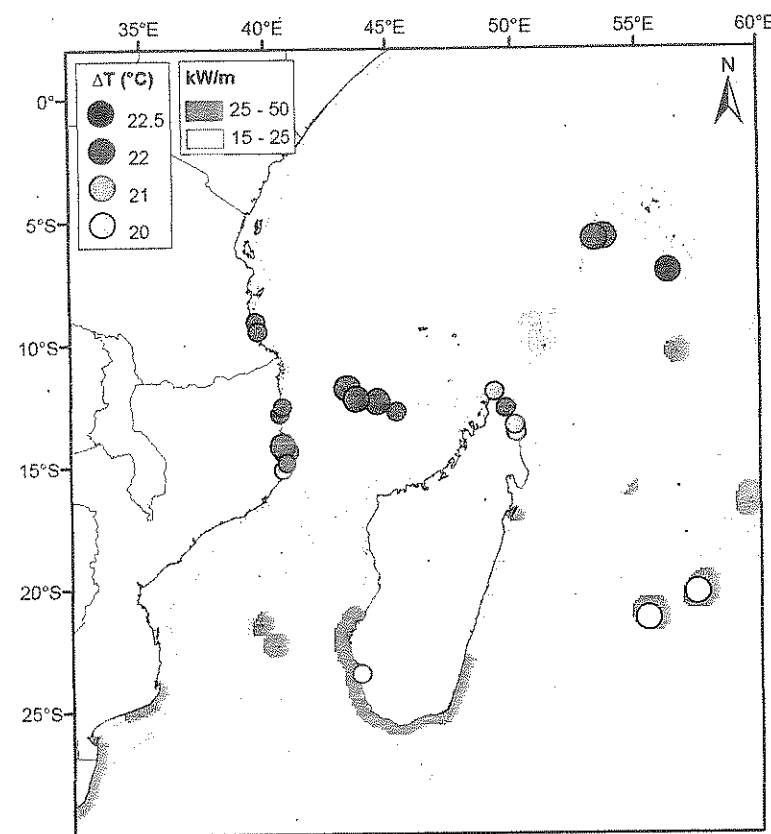


Figure 13 Map of coastal deep-water wave energy (green shades) and potential locations for OTEC (circles) in the Western Indian Ocean region. Larger circles indicate locations where temperature differences between surface and deep-water are found within 5 km from land. Smaller circles indicate locations where this distance is 5–10 km. Temperature differences and wave power magnitude are indicated in the legend. Figure adopted from Paper I.

tropical cyclones poses a major obstacle for utilizing this resource. Moreover, wave power levels in the Seychelles were classified as 'conditional', indicating that the resource is limited but may still be useful in some of the islands. The Seychelles are not exposed to cyclones and wave power is mostly derived from oceanic swell (long 'soft' waves), which is preferable for wave power.

'High' potential for land-based OTEC was found at eleven locations in the WIO. The most promising locations were identified in the Seychelles, Comoros, and northern Mozambique. These locations have an average annual temperature difference of $\geq 22^{\circ}\text{C}$ within less than 5 km from the shore. Due to seasonal variations in water temperature difference, the OTEC resource becomes less efficient during the southern monsoon. However, technical improvements such as the use of solar collectors to enhance temperature differences, make OTEC a potentially important future energy source for large-scale electricity production and seawater desalination (desalinated water is a by-product of some OTEC designs).

The potential for tidal power was found to be comparatively low. Tidal ranges vary greatly between different areas of the WIO but the potential for the resource was at best classified as 'conditional'. The highest tidal range was found in central Mozambique, but this region is characterized by estuarine coasts with high sedimentation rates and fringing mangrove forests. High sedimentation reduces the efficiency of tidal barrages, and mangrove forests in Mozambique are protected for their natural value. Other regions with 'conditional' potential for tidal barrages were found in northern Mozambique and western Madagascar. These areas have more suitable coastal features and thus, it may be possible to implement small-scale tidal barrages for off-grid electricity systems.

Seven locations with strong tidal currents were identified in Mozambique, Tanzania, and Kenya. It is likely that other (unknown) locations with strong tidal currents exist, but it could not be concluded that the WIO tidal currents are suitable for large-scale tidal current turbines. As an alternative, a micro-scale approach to tidal current turbines can provide useful amounts of electricity for decentralized grids in moderate tidal currents (see 4.4.1.). However, no high abundance of strong tidal currents was identified in the investigated areas.

The potential for ocean current power was difficult to assess due to the limited data available. The most promising regions for ocean current power are northern Mozambique and Kenya, but extractable levels of current speed could not be confirmed through the available data.

► Papers I and II indicated that natural resources for wave power and OTEC are available in the WIO region. Other ocean energy resources are less promising but may be of interest at particular locations.

With the physical prerequisites outlined, an obvious question is whether stakeholders – from policymakers to end consumers – will have interest and capacity to utilize emerging ocean energy technologies. Before turning to electricity demand and benefits, the socio-technical prerequisites will be examined.

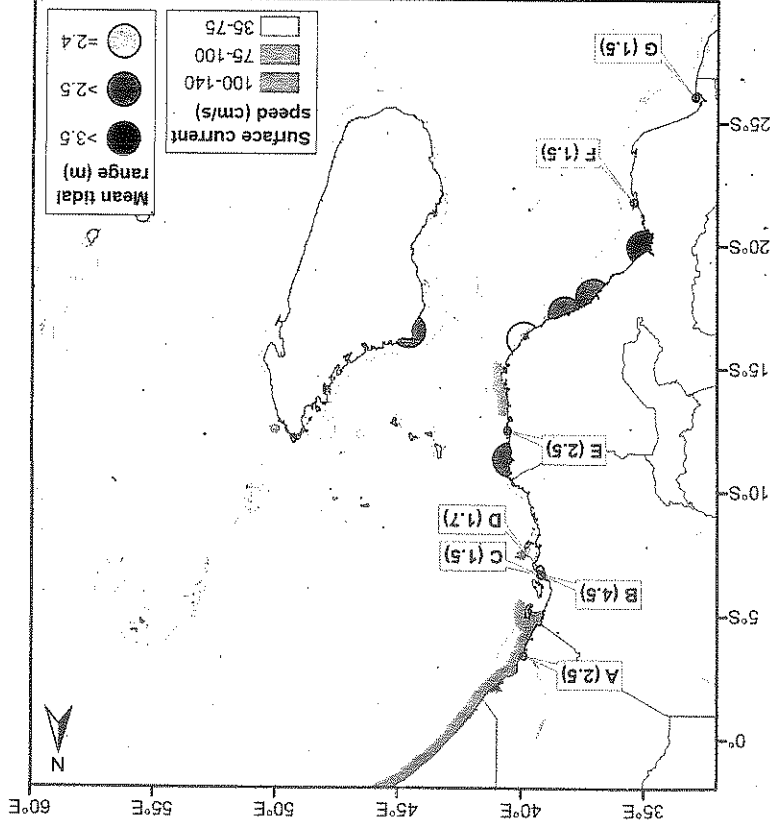


Figure 14 Map of coastal ocean current speed (green shades), mean tidal range (blue semicircles), and locations with strong tidal currents (labels) in the Western Indian Ocean region. Letters in tidal current labels indicate the local name of each location (see Paper I), while the numbers in brackets indicate the maximum spring current speed (m/s). Mean tidal range and ocean current speed are indicated in the legend. Note that tidal range semicircles only indicate the location of origin of the data and not the extent of the tide (tides occur all over the region). Figure adopted from Paper I.

The meta-analysis in Paper I indicated that the WIO region has substantial ocean energy resources, as shown in Figures 13 and 14 (see also Table 8 in Paper I).

'High' resource-based potential for wave power technologies was based on the criterion of average annual deep sea wave power of $\geq 2.5 \text{ kW/m}$. This criterion was fulfilled throughout the southern parts of the WIO, with highest values in southern Madagascar (40–60 kW/m). Seasonal variations of wave power are generally fairly low in the WIO, but more intense during the southern monsoon (southern hemisphere winter). However, the occurrence of

5.3.2. Socio-technical prerequisites and barriers

Paper III addresses the socio-technical prerequisites for the use of ocean energy technologies in developing countries. In Paper IV, generic barriers to successful electrification were examined. Barriers can be understood as socio-technical prerequisites that have not been met. Both studies focus on the rural context.

Six issues of particular relevance for ocean energy in a developing country context were examined in Paper III: (i) limited access to detailed resource data (oceanographic measurements), (ii) limited access to technically trained personnel, (iii) lack of access to spare parts and equipment, (iv) importance of local engagement, (v) high economic value of technical equipment (risk of theft), and (vi) high vulnerability to alteration of ecosystem services.

Regarding access to resource data (i), not only do developing countries currently have limited availability to site-specific measurements of ocean energy resources, but long-term measurements are very costly and add to investment costs, which are an important barrier to diffusion of modern energy technologies in developing countries (Karakosta *et al.* 2010, Ayub *et al.* 2011). This problem was specifically addressed in Paper II, and a method that can reduce the initial costs for implementation of small tidal power devices is suggested.

The lack of engineers (ii) and trained technical staff in rural areas is a major obstacle. In Mozambique for example, the native African population was strongly oppressed by colonial power and, when liberation occurred in the 70's, the country was left with very few citizens with higher education. Following the devastating civil war, which ended in 1992, the education system improved dramatically, but there is still a shortage of technically trained people, which additionally are rarely found in rural areas. Equipment (iii) such as adequate vessels or tools, of high technical standard, can be inaccessible in rural areas (Ehnberg 2006). For small ocean energy devices to operate in rural areas, a minimum number of devices is necessary to make the presence of technical professional personnel with their own equipment affordable, *i.e.* most of these systems cannot run fully on local basis, and single installations are likely to fail. The installation of multiple devices may also increase local familiarity with the technologies and increase local acceptance and engagement (iv). It is important to encourage engagement because it may also improve management and reduce the risk of theft (v) (Sheya and Mushi 2000). Project initiatives should preferably come from the locals and the power system should partly be owned by local stakeholders. But rural-living people cannot be expected to invest more than symbolically, and private investors are not interested in rural electrification, as was further indicated in Paper V. Bottom-up driven projects of energy technologies with high capital costs, such as most ocean energy technologies are therefore hard to foresee.

Finally, the livelihood of coastal rural communities is strongly dependent on the natural environment (vi), such as mangroves, sea grass meadows, coral reefs, and other marine ecosystems (Sinclair and Richmond 2002, Lange and Jiddawi 2009). For any ocean energy technology to be accepted in a rural coastal context there must be no compromising of the recognized ecosystem services. This may restrict the development of tidal barrages in particular, but it may also restrict the use of other ocean energy devices that are found to or believed to harm the environment or interfere with traditional activities.

► It was concluded in Paper III that all investigated ocean energy technologies required technical adaptations if they are to respond to the examined socio-technical prerequisites for small-scale use. It is likely that only devices with easily accessible generators, simple installation, and low environmental impact will have a chance to become appropriate for the market niche of small-scale electricity supply in developing countries. To date, a number of companies have approached this development path and are now developing robust, easily maintained systems for remote area electrification and desalination (Ayub *et al.* 2011, EWE 2011). For ocean energy technologies to be used in the market niche of rural electrification, constructive dialogues between developers, implementers, and researchers are necessary – as suggested by CTA methodology.

Based on energy sector actors' reflections, numerous barriers to successful rural electrification were identified in Paper IV. Most of the socio-technical prerequisites discussed above (Paper III) were mentioned by the actors. Among other important barriers were: low institutional quality (vii), inadequate planning capacity (viii), poverty and a poor rural market (ix), scattered rural populations (ix), and donor dependence (x).

Many developing countries have low institutional quality (vii) (Paimuly 2001, Dagbjartsson *et al.* 2007, Mulder and Tembe 2008). For example, this means that top-down management may reduce the efficiency of local or regional institutions, or that the legal frameworks might be underdeveloped. Both Tanzanian and Mozambican actors reported that inadequate planning (viii) can lead to uncoordinated rural development efforts and reduced outcomes from electrification. For example, if power is supplied, complementary services such as infrastructure, financial institutions, and access to appliances, should also be available. This issue is linked to rural poverty (ix) – electricity customers may simply not have access to investment capital even for small machinery or other productive uses, leading to low use of electricity and little economic development. Energy sector actors regarded rural poverty as a major barrier to electrification. Micro-finance should be available. It was further stressed that low population density (ix) in rural areas is problematic. Line extensions and substations make rural electrification very expensive in many areas (Haanyika 2008) and it was argued by some of the interviewed actors that electrification in these areas is not likely to be affordable.

It should be recalled that there is no generic definition of 'rural areas' but that it commonly means areas outside cities and towns, often characterized by more or less scattered populations (Hewitt 1989).

Mozambique and Tanzania, as well as many of the other countries in the WJO, are heavily dependent on international donors (x) for funding electrification in general, and rural electrification in particular. This was regarded as a problem among actors, even though all available funding is not always expended due to institutional insufficiencies. As an example, in Tanzania the authorities encourage the private sector to get involved in the power sector, but financial support from donors is not available to private operators.

► In conclusion, Paper IV shows that there are many barriers to rural electrification and introduction of energy technologies. Most of these barriers are related to institutions and should be addressed at a policy level.

Many of the problems discussed above are less important for large-scale projects. Larger energy systems are run continuously by expert staff with access to technical facilities and logistics. Parallels can be drawn with the large hydropower stations which operate in the WIO. Still, effective technology transfer is necessary for renewable energy projects – large and small-scale – to multiply in a host country (if the technology is not developed in the country) (Duic *et al.* 2003, Doukas *et al.* 2009). Technology transfer includes both hardware and 'know-how', such as manufacturing and supply chain capacity, institutional capacity, and social networks between all parts of the process (Karakosta *et al.* 2010). This is of high relevance for countries with no involvement in ocean energy development (which includes most countries in the world), and of less concern for countries taking part in the early development of the technology (e.g. India and China). The former is the case for almost all countries in the WIO. The exception is Réunion (a French island situated east of Madagascar) which is involved in the development of ocean energy (Krock 2010). Possibly, this experience may generate spin-off effects among neighbouring islands.

One important barrier to effective technology transfer to developing countries is that technology suppliers tend to lack knowledge about the recipients' (local customers and power sector actors) needs and capabilities (Karakosta *et al.* 2010). These issues, local electricity demand and perceptions among power sector actors are discussed in section 4.6.

5.4. Benefits of ocean energy to the WIO region (Step 4)

Electric power carries several social and health-related benefits⁴ and is one of several prerequisites for economic development (see 2.1). But what 'kind' of electricity is required, and how could ocean energy technologies contribute to meet the demand? This will be dealt with in the next two sections, divided into small-scale (off-grid electrification) and large-scale (main-grid supply) perspectives.

5.4.1. Benefits from small-scale ocean energy

In Paper IV it was indicated that the main drivers to rural electrification in the WIO are political ambitions and growing electricity demand among rural people (according to power sector actors interviewed in Tanzania and Mozambique). It was also argued that access to electricity in rural areas improves health and education and slows down urbanization. These suggested 'social' benefits of electrification are supported by the vast literature on rural electrification (see Papers IV and V). Not much power is required to satisfy this household-level demand; the domestic power consumption in rural Tanzania and Mozambique is about 100–300 W per household (Blenmow 2004, VPC 2008). It should also be noted that use of electricity – may – eventually ease the pressure on local environments such as forests and

mangroves used for charcoal production; but such energy transition is slow to take place (Mabubansi and Shackleton 2006, Prasad 2008). Economic development is expected if electricity is used for improving the output from agriculture, manufacturing, or business (*i.e.* productive use). This was agreed among energy sector actors in both Tanzania and Mozambique; most interviewees expressed the importance of increasing the productive use of electricity in rural areas (Paper IV and V). However, complementary services linked to rural development (e.g. micro-banks, electric appliances, and infrastructure) must be provided simultaneously for the catalytic-effect to ensue – for noteworthy finding from Paper V is that coordination between rural electrification and other rural development is currently low – potentially impeding productive use and economic growth from electrification.

Typical productive uses in Tanzania and Mozambique include processing mills, manufacturing workshops, fish markets, small businesses, and tourism. Electricity supply to rural industries is considered particularly beneficial; however, rural industries are still very rare in these countries. The power capacity required to supply small/micro-scale productive use is in the range of 1–20 kW per activity unit (Blenmow 2004). Rural industries require higher power capacity. For example, 250 kW supplies a stone quarry (Blenmow 2004); cotton processing factories require 50–1000 kW (VPC 2008). The interviewed power sector actors frequently mentioned that energy sources with low capacity, like solar PV, were problematic in that they could not be used for productive purposes (Paper IV and V). It was clearly shown that energy sector actors were more positive towards small-scale hydro than to other renewable energy technologies because hydropower generates enough power for productive use, and is a reliable power source.⁵

Single units of wave power and tidal current turbines have power capacities of about 20 to 2000 kW, and capacity factors⁷ of 20–40% (Johansson *et al.* 2004). A micro-scale approach, with installation of one or several ~25 kW devices (wave power, tidal current turbines, or micro tidal barges), can provide enough power for both domestic and productive use. This was exemplified in Paper II, where the intermittent but predictable power output from a micro tidal current turbine in moderate Mozambican currents was estimated to be 2.4 MWh per month. To ensure continuous access to power, micro-scale ocean energy systems should be complemented with other energy sources or efficient solutions for energy storage. However, where power is needed for controllable loads only (e.g. desalination, water-pumping, and grinding), even tidal power can be used without much backup.

The interviewed power sector actors had very different opinions on off-grid rural electrification (Paper V). Some respondents associated off-grid electrification with high costs and unreliable generation, an opinion that was particularly articulated in Mozambique. Other respondents regarded off-grid electrification as a necessary and important way of reaching out to remote areas. Most actors agreed that off-grid electrification based on renewable sources is

⁴ In addition to productive use and reliability the positive attitude to hydropower may reflect the familiarity of this source because large-scale hydropower is used in both Tanzania and Mozambique.
⁵ The capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full capacity.

advantageous in comparison to diesel-based off-grid electrification, which is currently the most common solution. Diesel generators were criticized by all actors.

► In addition to the general 'social' benefits of electricity, small ocean energy systems have enough power capacity to enable productive use of electricity in off-grid systems. Considering the extremely low rural electrification rates and the extensive coastlines of mainland WIO countries and Madagascar, this is where potential benefits from small-scale off-grid use of ocean energy would be highest.

5.4.2. Benefits from large-scale ocean energy

OTEC plants, tidal barrages, wave and tidal power farms, and ocean current power can be used for large-scale power generation. Such systems are typically expected to be deployed with capacities in the order of tens to hundreds of megawatts. Currently, all countries in the WIO have national peak consumptions below 1 GW, but consumption is expected to rise dramatically during forthcoming decades (Bugaje 2006). Large-scale ocean energy systems can contribute with a large share of the national electricity production in these countries (Paper I). For example, one OTEC plant of 10 MW⁸ would cover all of Comoros' current national electricity consumption, and a tidal barrage of 20 km² would generate 10% of Madagascar's current electricity consumption.

► Sub-Saharan Africa is challenged by an energy crisis that threatens to hamper development; to make use of available renewable sources is a necessity (Bugaje 2006). Ocean energy technologies may become important sources of electricity for some countries in the WIO. With reference to Paper I, the highest potential benefits from large-scale ocean energy can be found in the small island states of the WIO (Comoros, Mayotte, Seychelles, Réunion, and Mauritius). But in theory, large-scale ocean energy can also supply main grids in the mainland countries.

5.5. Adverse consequences of ocean energy (Step 5)

In Paper VI, a hazard identification and risk-ranking was conducted for wave power, tidal power, and OTEC. Importantly, the assessment only included published peer-reviewed articles of which very few presented their own data or referred to actual measurements from ocean energy systems. This lack of data has been highlighted in recent publications, with urgent calls for more research (Frid *et al. in press*, Inger *et al.* 2009). Keeping this in mind, the risk ranking exercise in Paper VI proposed that wave power and tidal current turbines pose their highest risks for marine mammals, followed by birds and fish. By contrast, OTEC poses higher risks for fish, followed by plankton. These results may reflect scientific worries rather than actual levels of hazard. Furthermore, the high degree of uncertainties together with the

young age of this field of research, may result in circular-referencing and propagation of possibly erratic assumptions. More detailed analyses are required.

If environmental impact assessments are to embrace an ecosystem-based perspective, which has been suggested in recent literature (Douvere 2008, Ehler and Douvere 2009), ecological risks should be analysed with prime focus on ecological processes, rather than single species (Paper VI). Such important ecological processes may be related to ecosystem resilience and ecosystem services. In this context, the most important assessment endpoints for ocean energy impacts would be those of key importance to prevent alteration of ecological regimes. These may be large predators, which are sensitive to environmental changes due to their low reproductive rates, and important for avoiding cascade effects down the food-web. Another example are structure-forming species such as corals or sea grasses, which maintain habitats for other species. Important endpoints to consider for wave and tidal power should be migrating whales or foraging dolphins and sharks. For OTEC, corals and biogeochemistry (e.g. nutrients) should be the prioritized endpoints.

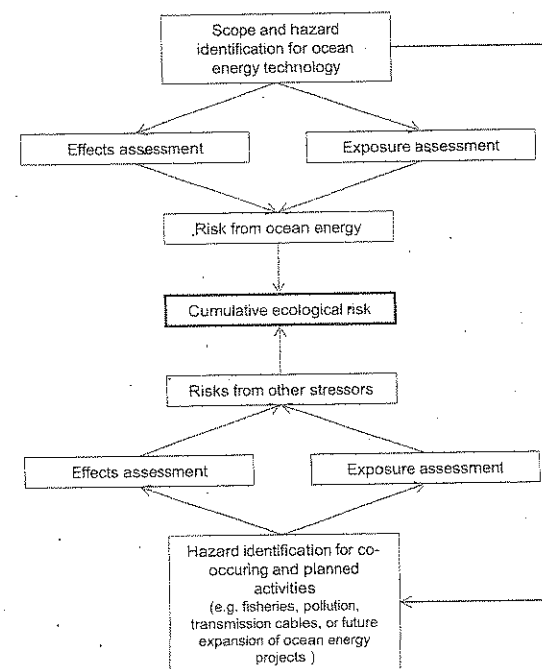


Figure 15. Conceptual model of the suggested framework for incorporating cumulative effects in EcoRA of ocean energy technologies. The upper four boxes constitute the basic Ecological Risk Assessment (EcoRA) procedure, including scope, hazard identification, effects assessment, and exposure assessment. The lower four boxes constitute the suggested way of including cumulative risks from other stressors in the assessment. Illustration adopted from Paper VI.

⁸ The capacity factor of an OTEC plant is 70–80% (Johansson *et al.* 2004)

Furthermore, the manifold exploitation of the ocean motivates the inclusion of multiple stressors (cumulative effects) when assessing ecological risks – although this is rarely done in practice (Halpern *et al.* 2008a, Wilhelmsson *et al.* 2010). Paper V outlines how the Ecological Risk Assessment framework (EcoRA) (Suter and Barnhouse 1993) can be used for structuring ecosystem-based risk assessments and account for cumulative impacts. The suggested procedure is illustrated in Figure 15.

Examples of multiple stressors of relevance for OTEC developments in the WIO could be nutrient discharge from land, or coral mining, or dynamite fishing. A small OTEC plant displaces 50–100 m³ per second of nutrient-rich water from the deep sea to 100–200 m depth. If this water displacement poses a risk to nearby coral reefs, this risk may be non-linearly inflated by simultaneously operating or expected stressors; particularly so if stress-levels are already close to threshold values.

An example of relevant multiple stressors in the case of tidal current turbines in the WIO could be shark fisheries: it is not known how large animals are affected by the rotor blades of open tidal current turbines (rotor tip speed up to ~10m/s) but sharks may be attracted to moving objects and electric devices, fast-flowing currents are natural habitats for sharks, the illegal shark fishery in the WIO is alarmingly large and consequently, the effects from potential tidal turbines on sharks may be underestimated if the fisheries effects on the same population are not included in the risk analysis.

Although some ideas on how to improve the assessment of environmental impacts of ocean energy have been suggested in Paper VI, it is difficult to extrapolate the weak scientific basis for potential ecological impacts into impact/risk assessments. However, on a very generic level and based on the limited data available, the expected impacts from wave power seem fairly low (Langhammer *et al.* 2009, Langhammer *et al.* 2010, Palha *et al.* 2010). Tidal barrages, tidal current turbines, OTEC, and ocean current power give rise to larger concerns. Tidal barrages exploit intertidal mudflats of high productivity and potential ecological value. Tidal current turbines require fast-flowing currents which often occur in narrow passages that constitute habitats of importance to foraging predators. Land-based OTEC requires narrow continental shelves, areas known for their particularly high productivity, and displace enormous amounts of water. Ocean current power also requires narrow continental shelves and the fast-moving turbines may potentially interfere with marine mammals.

The WIO is one of the least affected areas of the oceans and comprises a multitude of ecosystems where above-mentioned concerns might be highly relevant. For example, the marine ecosystems on the narrow shelf of northern Mozambique present great natural value related to pristine coral reefs and whale migration (Sinclair and Richmond 2002). Fringing mangrove forests protect much of the East African coast from erosion and comprise some of the coral reefs most worthy of protection in the world (Molina *et al.* 2011). In addition to the ecological values, coastal waters are used for fishing and transport (Sinclair and Richmond 2002), hence deployment of larger energy systems may become an issue of sea use.

► In Paper VI it is concluded that the knowledge-base of impacts from ocean energy technologies is very limited and that, until the knowledge has improved, assessment methods that accounts for uncertainties and transfer of impact-data between fields of activities are important to develop and use. Methodologically, it is suggested that ecological risk assessments should focus on ecological processes and key endpoints rather than single species. Furthermore, cumulative effects should be included in analyses. In essence, the WIO possesses enormous marine ecosystem values, directly linked to coastal livelihood, and adverse consequences from any ocean/coastal activities must be thoroughly considered.

While ecological risk assessments and other impact assessment methods operate at a case-specific – often project-specific – level, TA-thinking also provides the opportunity to address the larger picture of risk. Once a power generating device has been deployed in the water it will pose whatever risks it carries until the end of its operation. Therefore, the task for a risk assessor is to try to predict the potential risks with as high accuracy as possible. But at the resource level, Collingridge's dilemma becomes very relevant. Collingridge warned about the difficulties in predicting (societal) effects of technologies and suggested that emphasis should be put on mitigation and late adaptation of technologies. When extrapolating to the ecological context (which can be motivated by the complexity of ecosystems and cumulative impacts), this means that we must strive to keep technological diversity in the ways we utilize a given resource. Since wave power and tidal current turbines currently provide far higher technological diversity than any other ocean energy technology, utilization of wave and tidal current resources may carry lower long-term risks. With focus on these ocean resources, technology can be more easily adapted in case adverse consequences become obvious. A global promotion of the OTEC technology (which is not very technically diverse), for example, may become a lock-in if adverse effects appear.

6. POLICY-ORIENTED SUMMARY OF RESULTS (STEP 6)

This thesis does not provide weighted analysis of policy options, as should be the outcome of a full TA. Instead, the result is discussed from a small-scale (6.1.) and a large-scale (6.2) perspective. The result should be regarded as a basis for future assessments of ocean energy for developing countries. A brief summary is given in Table 1.

6.1. Small-scale ocean energy in the WIO

Small-scale use of ocean energy in the WIO offers potential benefits to many remote coastal communities in the mainland countries of the region, and possibly also the small islands of, for example, the Seychelles (Paper I). Small-scale ocean energy can provide enough power for productive uses (Paper I-II) and has relatively low intermittency (although tidal power has high variability) (Doukas *et al.* 2009). With load-based control systems (Ehnberg 2007), including productive possibly controllable loads such as milling or water pumping, ocean energy can provide benefits through off-grid electrification, preferably in combination with other renewable energy sources.

For small-scale ocean energy developments in the WIO to be realized, several socio-technical prerequisites have to be met and technical adaptation must take place in the direction of simplicity (regarding installation and maintenance), even though it may come at the cost of lower efficiency (Paper III). This approach has already been taken by some technology developers aiming for this specific market niche (Charlier and Justus 1993, Ayub *et al.* 2011, EWE 2011, GHT 2011). In addition, there are several generic institutional barriers for small-scale energy technologies to be successfully implemented in rural areas (Paper IV). These barriers can be addressed at the policy level, and may improve with time. Also, the poor rural markets and the lack of private sector interest may improve within the timeframe of this study (2050). However, at the current state of affairs, small-scale ocean energy would meet many challenges in the WIO.

The knowledge base regarding ecological consequences of small-scale ocean energy technologies is weak and therefore, adverse effects are difficult to predict. More research is needed.

6.2. Large-scale ocean energy in the WIO

The most obvious matches between prerequisites for, and benefits of, ocean energy in the WIO are found in large-scale OTEC and wave power in the small island states (Comoros, Mayotte, Réunion, Mauritius, and Seychelles) (Paper I). Regarding the direct benefits to customers and to the electricity grid, OTEC technology has the advantages of high capacity (10–100 MW per plant), low intermittency of power, the production of potable water as a by-product, and greater resistance to tropical cyclones than other, exposed, devices. Wave power has lower expected costs and has reached farther in technical development. The adverse ecological consequences are not well known for any of the technologies, although the limited available data indicate low impacts of wave power (Paper VI).

If development of wave power or OTEC takes place in one of the more affluent islands (e.g. Réunion) successful projects may spread to other islands (e.g. Mauritius, Comoros). CDM and similar post-Kyoto protocol agreements are likely to be important drivers for such developments. For investors to finance ocean energy in developing countries they require a secure energy market and fixed feed-in tariffs (Doukas *et al.* 2009), which in turn require a developed power sector with high institutional quality. This potential barrier may be reduced with time, as a consequence for institutional development. However, OTEC may also pose substantial risk to marine ecosystems.

An interesting case is the Comoros, where OTEC seems to be the most promising ocean energy technology. OTEC plants of relatively small size could become suitable prime sources of energy and freshwater for the country (Paper I). If this potential resource should be taken into serious consideration, regulatory authorities must take great notice of the basically unknown and potentially significant, or even immense, ecological effects that OTEC developments may entail to fragile coastal ecosystems. This leads to the core of TA – how should potential benefits be weighed against uncertainties and risk? This has not been dealt with in this thesis.

Table 1. Summary of findings from the WIO case-study, and possible generic contributions to the wider developing country (d.c.) context.

Western Indian Ocean Findings		Extrapolation to the wider d. c. context	
Paper I	The match between natural resources and power sector demand is highest in the small island states (large-scale) and in remote coastal areas of the mainland countries (small-scale)	Paper I	Ocean energy natural resources are available, particularly for wave power and OTFC
Prerequisites		Prerequisites	
Papers II - III	Socio-technical prerequisites must be met both by technology adaptation and facilitated resource assessment methods for small-scale ocean energy to be of interest for the rural electrification niche market	Papers II - III	Complementary services are required for productive use of power to thrive (small-scale ocean energy should therefore be part of rural development)
Papers II - V	Technical adaptations may improve the usefulness of small-scale ocean energy in the rural electrification niche market; a method for low-cost estimation of micro-tidal potential have been suggested	Papers II - V	Links between technology, productive use, and rural development are important for small-scale power sources (incl. ocean energy)
Paper IV	Several barriers (often institutional) complicate the use of small-scale energy systems and off-grid electrification	Paper IV	The power sector quality may hinder project development and must be thoroughly considered
Benefits		Benefits	
Paper I	Ocean energy is available in coastal areas where other energy sources are less available	Paper I	Ocean energy has benefits related to power quality (relatively high predictability); small-scale wave power and tidal power can be used for purposes related to economic development (e.g. using load-based control systems); OTFC and ocean current power have very high power quality (stable and predictable power output) that can be particularly useful sources for large grids
Papers II - V	All ocean energy has benefits related to power quality (relatively high predictability); small-scale wave power and tidal power can be used for purposes related to economic development (e.g. using load-based control systems); OTFC and ocean current power have very high power quality compared to many other renewable energy sources	Papers II - V	Ocean energy have high power quality compared to many other renewable energy sources
Adverse consequences		Adverse consequences	
Paper VI	Ecological effects of ocean energy are not well known	Paper VI	Ecological effects of ocean energy are not well known
Paper VI	It is important to consider ecological processes and cumulative effects in ecological risk assessments	Paper VI	It is important to consider ecological processes and cumulative effects in ecological risk assessments
Generic	The marine ecosystems of the WIO provide ecosystem services of direct importance to coastal populations	Generic	The marine ecosystems of the WIO provide ecosystem services of direct importance to coastal populations

7. REFLECTIONS

7.1. TA framework

Energy system modelling and economic analyses were not in focus in this thesis. Such analyses are a necessity for detailed country- or project-specific studies; this means that in-depth studies require a stronger Energy Technology Assessment (ETA) approach.

The dialogue with European ocean energy developers have been a natural part of this work. parts, both regarding the understanding of prerequisites and ecological risk. Communication of results and feedback would benefit both research and technology adaptation. The Constructive Technology Assessment (CTA) approach strives towards risk reduction through proactive technology adaptation. Considering Collingridge's dilemma and the need for late adaptations in case of adverse consequences, the CTA approach is a valuable branch of TA (even though it does not provide any full risk reductions). Based on the limited understanding of ecological risks and the critical state of the oceans, CTA should be promoted among ocean energy developers.

The Environmental Technology Assessment (ETA) framework in its current shape implies a workshop-structured continuous dialogue with host-country stakeholders, which has not been followed in this study. This branch of TA, most actively promoted by UNEP in the early 2000's, seems to have gone out of practice. However, as argued by Coates (1998), the ETA emphasis on local environmental impacts and the focus on developing country contexts are increasingly relevant. ETA should be developed so that it becomes more practical.

TA was developed as a policy-supportive procedure and not necessarily as a research methodology. Research, however, may be necessary to find foundation for assessments in fields where the knowledge base is weak, i.e. less-studied matters which have been outside the focus of previous research, policy-makers, enterprises, and the public (Ely *et al.* 2011).

The links between technology development, organizations, economics, legislation, and politics have not been thoroughly addressed in this work; these issues will be important for more detailed analyses (La Porte 1997).

Although the core purpose of TA, to provide weighted analyses of policy option, have not been covered in this work the overarching aim and procedure of the TA framework has been suitable for weaving together the highly multidisciplinary aspects necessary for meeting the objective of the thesis. Perhaps TA-thinking can provide valuable perspectives in a time of increasing use of ocean space and resources?

7.2. The way forward

Despite a wide scope, the appended studies in this thesis focus more on physical and socio-technical prerequisites and benefits, and less on adverse consequences. However, there is an urgent call for further research on ecological impacts from ocean energy technologies (Frid *et al. in press*, Inger *et al.* 2009, Langhamer *et al.* 2010).

Modern ecology emphasises ecosystem functions and resilience, where human interactions and interests are regarded as part of the system. In marine science there are trends towards ecosystem-based management and spatial planning (Crowder and Norse 2008, Douvère 2008). In this context, it would be relevant to investigate how these issues can be intertwined in practice: how to incorporate ecosystem-based management and consideration of cumulative effects in marine spatial planning? A hypothesis, outlined in Paper VI, is that the EcoRA framework is a suitable methodology that can be developed in this direction. The EcoRA is structured in a way that facilitates systems thinking (important for ecosystem-based management), it focuses on endpoints rather than technologies (important for addressing cumulative effects), and it can be used both qualitatively and quantitatively (important for marine spatial planning and risk analysis).

However, assessment methodology is not the only field in need of development. Empirical data is needed to reduce uncertainties. One of the most obvious concerns is how marine fauna is affected by open flow tidal current turbines. Tidal turbines are to be deployed in areas important to large fish and marine mammals and turtles – it is not known to what degree these animals can avoid the fast-moving rotor blades. Another area of concern is the ecosystem effects of OTEC plants which discharge thousands of litres water per second at altered temperatures and content of nutrients.

We will never be able to foretell all consequences to an ecosystem, but neither can we leave it without a try. The social control of the oceans is increasing – it is an opportunity. With the successful development of policies based on robust methods able to assess effects associated with high uncertainties, the collection of empirical data on impacts, and the use of adaptable technologies, the future utilization of ocean resources should be less detrimental to marine ecosystems than history has shown previous utilization to have been.

ACKNOWLEDGEMENTS

I wish to thank all my Tanzanian and Mozambican collaborators who have made this work possible, and have taught me so much – from oceanography to power sector inquiries. In particular, I am grateful to Prof. Boaventura Cuamba, Dr. Alberto Mavume, and Mr. Francisco Francisco at Universidade Eduardo Mondlane, and Dr. Cuthbert Kimambo and Mr. Said Ibrahim at University of Dar es Salaam. Thank you Paula Oksanen for your invaluable assistance in the far North. Thank you Dr. Gabriel Albano and staff for your great hospitality and professional assistance at Inhaca Biological Station, and most of all, thank you for recovering Paulito from murky sharky waters.

Thank you Joan Major for your hospitality and your kind caring for us Swedes from the very first day and on; thank you Örjan and Liduva Vilén for letting me enjoy/interrupt your first shiny days together. Thank you Gabbe for our adventures in car and sea grass. So far so good, Africa, I am as grateful as surprised of still being with all my limbs – thank you creatures of the Western Indian Ocean!

I am very grateful to Stiftelsen Futura, the main funder of this project and STEEP-RES, and to ÅForsk, Adlerbertska stiftelserna, and Chalmersska Forskningsfonden. And thank you ESA and Anne-Marie Tillman for encouraging support.

...mer tack

Tack Sverker för de stora perspektiven – och att du lärt mig hur ofarliga vilda djur kan vara, tack Jimmy för de små perspektiven – och för att du lärt mig alla hightech verktyg (Matlab och Skype asså). Tack också för ditt stöd Jimmy. Tack Martin för de djuriska perspektiven – och för att du visat mig Afrika. Tack Rutger för att du gav mig chansen att pröva mina vingar – eller kanske snarare labbar. Tack Inês för helt ovärderlig hjälp, kärlek och whiskey. Tack mamma för ett lexikon om det engelska språket, tack pappa för fisken som närt min hjärna. Tack lillebror och hela övre Majorna för socialt stöd och bröd. Tack minibror för att du 'vaktade' mig på ambassaden och snorklade längre ut än mig i hajvattnet. Tack Slangen och Sandra för historisk skolning i stresstålighet, och för löpande omvärldsanalys. Tack Sting och Mia för att ni förstår det sköna i industri – tack Umeå för att ni förstår det sköna i natur. Tack Robin för att du inte är anti... Tack Fidge för att du kanariefäglade huruvida biologer kan leva på Chalmers. Tack Kathrine som var ett så trevligt inslag i 'miljömuppeland'. Och tack mina kära doktorandkollegor som så ömsint, och i varierande utförande, sett till att jag ätit ordentligt. Tack Helene för att du är min kollega#1, samt har lärt mig vad en institution är för något (tror jag).

EWURA. 2011a. Appendix 2A Detailed tariff calculations for year 2011 for the sale of electricity to the main grid in Tanzania under standardized small power purchase agreements in Tanzania. Energy and Water Regulatory Authority, Dar es Salaam.

EWURA. 2011b. Appendix 2B Detailed tariff calculations for year 2011 for the sale of electricity to the mini-grids in Tanzania under standardized small power purchase agreements in Tanzania. Energy and Water Regulatory Authority, Dar es Salaam.

FAO. 2010. The State of World Fisheries and Aquaculture. Food and Agriculture Organization of the United Nations, Rome.

Ferro, B. D. 2006. Wave and tidal energy: Its Emergence and the Challenges it Faces. *Refocus* 7:46-48.

Finkl, C. W. and R. Charlier. 2009. Electrical power generation from ocean currents in the Straits of Florida: Some environmental considerations. *Renewable and Sustainable Energy Reviews* 13:2597-2604.

Fraenkel, P. L. 2002. Power from marine currents. *Proceedings of the Institution of Mechanical Engineers* 216:1-14.

Frid, C., E. Andonegi, J. Depestele, A. Judd, D. Rihan, S. I. Rogers, and E. Kenchington. The environmental interactions of tidal and wave energy generation devices. Environmental Impact Assessment Review In Press, Corrected Proof.

Gajanayake, P. A., A. Furukawa, and K. Okuma. 1998. Applicability of Darrieus-Type Turbine for Extra-Low Head Tidal Power Generation. in Proceedings of the Eighth International Offshore and Polar Engineering Conference. *The International Society of Offshore and Polar Engineers*, Montréal.

Gamman, J. K. 1994. Overcoming Obstacles in Environmental Policymaking Creating Partnerships Through Mediation. State University of New York Press, Albany.

GHT. 2011. The Gorlov Helical Turbine. Page <http://www.gcktechnology.com/GCK/pg2.html>.

Gómez, M. F. and S. Silveira. 2010. Rural electrification of the Brazilian Amazon - Achievements and lessons. *Energy Policy* 38:6251-6260.

Góralczyk, M. 2003. Life-cycle assessment in the renewable energy sector. *Applied Energy* 75:205-211.

Gorlov, A. M. 2001. Tidal Energy. *Academic Press*.

Griekspoor, W. 1981. Ocean thermal energy conversion. *Resources and Conservation* 7:49-60.

Gustavsson, M. 2007a. Educational benefits from solar technology--Access to solar electric services and changes in children's study routines, experiences from eastern province Zambia. *Energy Policy* 35:1292-1299.

Gustavsson, M. 2007b. With time comes increased loads--An analysis of solar home system use in Lundazi, Zambia. *Renewable Energy* 32:796-813.

Haanyika, C. M. 2008. Rural electrification in Zambia: A policy and institutional analysis. *Energy Policy* 36:1044-1058.

Hagerman, G., B. Zickefoose, and T. Heller. 1989. Wave energy resource and technology assessment for coastal North Carolina. Pages 755-760 vol.752 in Energy Conversion Engineering Conference, 1989. IECEC-89., *Proceedings of the 24th Intersociety*.

Halpern, B. S., K. L. McLeod, A. A. Rosenberg, and L. B. Crowder. 2008a. Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal Management* 51:203-211.

Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. P. Madin, M. T. Perry, E. R. Selig, M. Spaldig, R. Steneck, and R. Watson. 2008b. A Global Map of Human Impact on Marine Ecosystems. *Science* 319:948-952.

Hammons, T. J. 1993. Tidal Power. *Proceedings of the IEEE* 8:419-433.

Harvey, L. D. 2008. Mitigating the atmospheric CO₂ increase and ocean acidification by adding limestone powder to upwelling regions. *Journal of Geophysical Research* 113:1-21.

Hay, J. E. and M. Noonan. 2000. Anticipating the Environmental Effects of Technology: A manual for decision-makers, planners and other technology stakeholders. United Nations Environment Programme.

Hellström, T. 2003. Systemic innovation and risk: technology assessment and the challenge of responsible innovation. *Technology in Society* 25:369-384.

Hewitt, M. 1989. Defining "rural" areas : impact on health care policy and research. Office of Technology Assessment, Congress of the United States, Washington, D.C.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine & Freshwater Research* 50.

Holland, R., L. Perera, T. Sanchez, and R. Wilkinson. 2001. Decentralised rural electrification : Critical success factors and experiences of an NGO. *Refocus* 2:28-31.

Huitric, M., C. Folke, and N. Kautsky. 2002. Development and government policies of the shrimp farming industry in Thailand in relation to mangrove ecosystems. *Ecological Economics* 40:441-455.

IEA. 2007. World energy outlook 2007. International Energy Agency.

IHS. 2010. Global Ocean Energy Markets and Strategies 2010-2030. IHS Emerging Energy Research, Cambridge.

IHTADA. 2011. Alternative Energy Tanzania: Wave Power to Replace Gas in Zanzibar? The Power and Energy Reviews. Page <http://www.ihada.com/2011/05/alternative-energy-tanzania-wave-power-to-replace-gas-in-zanzibar/>.

Inger, R., M. J. Attrill, S. Bearhop, A. C. Broderick, W. James Grecian, D. J. Hodgson, C. Mills, E. Sheehan, S. C. Votier, M. J. Witt, and B. J. Godley. 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology* 46:1145-1153.

IPCC. 2007. Climate Change 2007: Synthesis Report. Intergovernmental Panel on Climate Change. Page http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

ITA. 2011. General remarks on technology assessment. Page <http://www.ocaw.ac.at/ita/>. Institute of Technology Assessment, Vienna.

Jacobson, A. 2007. Connective Power: Solar Electrification and Social Change in Kenya. *World Development* 35:144-162.

Johansson, T. B., K. McCormick, L. Neij, and W. Turkenburg. 2004. The Potentials of Renewable Energy: Thematic Background Paper. *International Conference for Renewable Energies*, Bonn.

Kanase-Patil, A. B., R. P. Saini, and M. P. Sharma. 2010. Integrated renewable energy systems for off grid rural electrification of remote area. *Renewable Energy* 35:1342-1349.

Karakosta, C., H. Doukas, and J. Psarras. 2010. Technology transfer through climate change: Setting a sustainable energy pattern. *Renewable and Sustainable Energy Reviews* 14:1546-1557.

Karekezi, S. and J. Kimani. 2002. Status of power sector reform in Africa: impact on the poor. *Energy Policy* 30:923-945.

Karekezi, S. and J. Kimani. 2004. Have power sector reforms increased access to electricity among the poor in East Africa? *Energy for Sustainable Development* 8:10-25.

Kaundinya, D. P., P. Balachandra, and N. H. Ravindranath. 2009. Grid-connected versus stand-alone energy systems for decentralized power--A review of literature. *Renewable and Sustainable Energy Reviews* 13:2041-2050.

Khan, J. and G. Bhuyan. 2009. Ocean Energy: Global Technology Development Status. Powertech Labs, Surrey.

Khan, M. J., G. Bhuyan, M. T. Iqbal, and J. E. Quaiocoe. 2009. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Applied Energy* 86:1823-1835.

Khan, M. J., M. T. Iqbal, and J. E. Quaiocoe. 2008. River current energy conversion systems: Progress, prospects and challenges. *Renewable and Sustainable Energy Reviews* 12:2177-2193.

Kowalik, Z. 2004. Tide distribution and tapping into tidal energy. *Oceanologia* 46:291-331.

Krock, H. 2010. Ocean Thermal Energy Conversion. World Energy Council, London.

La Porte, T. M. 1997. New opportunities for technology assessment in the post-OTA world. *Technological Forecasting and Social Change* 54:199-214.

Lamadrid-Rose, Y. and G. W. Boehlert. 1988. Effects of cold shock on egg, larval, and juvenile stages of tropical fishes: Potential impacts of ocean thermal energy conversion. *Marine Environmental Research* 25:175-193.

- Lange, G.-M. and N. Jiddawi. 2009. Economic value of marine ecosystem services in Zanzibar: Implications for marine conservation and sustainable development. *Ocean & Coastal Management* 52:521-532.
- Langhamer, O. 2010. Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden). *Marine Environmental Research* 69:374-381.
- Langhamer, O., K. Hailkonen, and J. Sundberg. 2010. Wave power--Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. *Renewable and Sustainable Energy Reviews* 14:1329-1335.
- Langhamer, O., D. Wilhelmsson, and J. Engström. 2009. Artificial reef effect and fouling impacts on offshore wave power foundations and buoys - a pilot study. *Estuarine, Coastal and Shelf Science* 82:426-432.
- Lenard, D. 2007. Ocean Thermal Energy Conversion. World Energy Council, London.
- Li, D., S. Wang, and P. Yuan. 2010. An overview of development of tidal current in China: Energy resource, conversion technology and opportunities. *Renewable and Sustainable Energy Reviews* 14:2896-2905.
- Lim, Y. S., and S. L. Koh. 2010. Analytical assessments on the potential of harnessing tidal currents for electricity generation in Malaysia. *Renewable Energy* 35:1024-1032.
- Madhubani, M., and C. M. Shackleton. 2006. Changing energy profiles and consumption patterns following electrification in five rural villages, South Africa. *Energy Policy* 34:4081-4092.
- Magesh, R. 2010. OTEC Technology - A World of Clean Energy and Water. In Proceedings of the World Congress on Engineering, London.
- Maher, P., N. P. A. Smith, and A. A. Williams. 2003. Assessment of pico hydro as an option for off-grid electrification in Kenya. *Renewable Energy* 28:1357-1369.
- Maina, J., T. R. McInnes, V. Vennus, M. Atweberhan, and J. Madim. 2011. Global Gradients of Coral Exposure to Environmental Stresses and Implications for Local Management. *PLOS ONE* 6:e23064.
- Mario, R. 2001. Ocean Thermal Energy Conversion and the Pacific Islands. 417. Suva.
- Martinez, E. 2001. Renewable energy investment by the World Bank. *Energy Policy* 29:689-699.
- Masali, D. C. P., S. D. Ababio, M. Beebejann, A. Diallo, E. K. Dovo, C. Manueta, J. Wedemge, B. O. Hamady, L. Scott, Z. Sohoun, A. K. Arnah, M. Theuri, R. Jasmit, H. On Ganda, and M. Brown. 2006. African Marine Atlas. Intergovernmental Oceanographic Commission.
- McIntyre, A. D. 1992. The current state of the oceans. *Marine Pollution Bulletin* 25:28-31.
- MEA. 2005. Ecosystems and Human Well-being: Synthesis. Millennium Ecosystem Assessment, Island Press, Washington DC.
- Meyers, S., N. Goldman, N. Martin, and R. Friedman. 1993. Prospects for the power sector in nine developing countries. *Energy Policy* 21:1123-1132.
- Mikkelsen, B. 2005. Methods for development work and research: A new guide for practitioners. Sage Publications, London.
- Ministerio. 2011. High Efficiency - Low Impact. Page <http://www.ministerio.com/>.
- Miser, H. J. and S. E. Quade. 1988. Craftsmanship in Analysis. Pages 3-26 in H. J. Miser and E. S. Quade, editors. Handbook of Systems Analysis. Elsevier Science Publishing.
- Moberg, A. 2006. Environmental systems analysis tools for decision-making: LCA and Swedish waste management as an example. Royal Institute of Technology, Stockholm.
- Morton, D. L. 2002. Reviewing the history of electric power and electrification. *Endeavour* 26:60-63.
- Mulder, P., and J. Tembe. 2008. Rural electrification in an imperfect world: A case study from Mozambique. *Energy Policy* 36:2785-2794.
- Nihons, G. C. and M. A. Syed. 1997. A financing strategy for small OTEC plants. *Energy Conversion and Management* 38:201-211.
- Olsson, M.-O., and G. Sjöstedt. 2004. Systems and systems theory. Pages 3-29 in M.-O. Olsson and G. Sjöstedt, editors. Systems Approaches and Their Application: Examples from Sweden. Luwer Academic Publishers, Dordrecht.
- Painuly, J. P. 2001. Barriers to renewable energy penetration: a framework for analysis. *Renewable Energy* 24:73-89.

- Palha, A., L. Mendes, C. J. Fortes, A. Brito-Melo, and A. Sarmiento. 2010. The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices. *Renewable Energy* 35:62-77.
- Peters, J., M. Harsdorff, and F. Ziegler. 2009. Rural electrification: Accelerating impacts with complementary services. *Energy for Sustainable Development* 13:38-42.
- PEW Oceans Commission. Charting a Course for Sea Change. A Report to the Nation.
- Pighi, M. and R. J. van der Plas. 2009. Innovative private micro-hydro power development in Rwanda. *Energy Policy* 37:4753-4760.
- Pillai, I. R. and R. Banerjee. 2009. Renewable energy in India: Status and potential. *Energy* 34:970-980.
- Praedle, D. 1984. Simple theory for designing tidal power schemes. *Advances in Water Resources* 7:21-27.
- Prasad, G. 2008. Energy sector reform, energy transitions and the poor in Africa. *Energy Policy* 36:2806-2811.
- Quayle, R. G. and M. J. Changery. 1981. Estimates of Coastal Deepwater Wave Energy Potential for the World. Pages 903-907 in *Oceans* 81, Boston.
- Qurashi, M. M. and T. Hussain. 2005. Renewable Energy Technologies for Developing Countries: Now and to 2023. Publications of the Islamic Educational, Scientific and Cultural Organization.
- Ranganathan, V. 1993. Rural electrification revisited. *Energy Policy* 21:142-151.
- Rodemeyer, M., D. Saretzky, and J. Wilsdon. 2005. The Future of Technology Assessment. Woodrow Wilson International Center for Scholars, Washington DC.
- Segurado, R., S. Pereira, A. Pipio, and L. Alves. 2009. Comparison between EMINENT and other energy technology assessment tools. *Journal of Cleaner Production* 17:907-910.
- Sheya, M. S. and S. Mushfi. 2000. The state of renewable energy harnessing in Tanzania. *Applied Energy* 65:257-271.
- Shitoyama, H., G. Yoshizawa, M. Matsuo, and T. Suzuki. 2009. Institutional options and operational issues in technology assessment: Lessons from experiences in the United States and Europe. Pages 1-6 in *Science and Innovation Policy*, 2009 Atlanta Conference on.
- Sinclair, P. and M. D. Richmond. 2002. People of the Coast. Pages 21-31 in M. D. Richmond, editor. A Field Guide to the Seashores of Eastern Africa and the Western Indian Ocean Islands. Sida/SAREC, Milan.
- Smith, H. D. 2000. The industrialisation of the world ocean. *Ocean & Coastal Management* 43:11-28.
- Sovacool, B. K. 2009. The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse? *Utilities Policy* 17:288-296.
- Spalding, M. D., H. E. Fox, G. R. Allen, N. Davidsen, Z. A. Ferdana, M. Finlayson, B. S. Halpern, M. A. Jorge, A. Lombana, S. A. Lourie, K. D. Martin, E. McManus, J. Molnar, C. A. Recchia, and J. Robertson. 2007. Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. *Bioscience* 57:573-583.
- Stratman, P. J. T. and W. G. J. H. M. van Sark. 2008. A new hybrid ocean thermal energy conversion-Offshore solar pond (OTEC-OSP) design: A cost optimization approach. *Solar Energy* 82:520-527.
- Suter, G. and L. Barnhouse. 1993. Assessment Concepts. in G. Suter, editor. Ecological Risk Assessment. Lewis Publishers, Michigan.
- TE. 2010. Tidal Electric: Harnessing the oceans' tides for commercial scale, predictable, cost-competitive renewable electric power. Tidal Electric Inc. Page <http://tidalelectric.com/>.

- Therivel, R. and B. Ross. 2007. Cumulative effects assessment: Does scale matter? *Environmental Impact Assessment Review* 27:365-385.
- Thomas, G. 2008. The Theory Behind the Conversion of Ocean Wave Energy: a Review. Pages 41-91 in J. Cruz, editor. *Ocean Wave Energy - Current Status and Future Perspectives*. Springer, Heidelberg.
- Tran, T. A. 2007. Review of Methods and Tools Applied in Technology Assessment Literature. Pages 1651-1660 in PICMET, Portland.
- Uehara, H., C. O. Dilao, and T. Nakaoka. 1988. Conceptual design of ocean thermal energy conversion (OTEC) power plants in the Philippines. *Solar Energy* 41:431-441.
- UNDP. 2007. Energizing the Least Developed Countries to Achieve the Millennium Development Goals: The Challenges and Opportunities of Globalization. United Nations Development Programme, Istanbul.
- UNEP. 1983. Ocean energy potential of the West African region. United Nations Environment Programme.
- UNFCCC. 2011. United Nations Framework Convention on Climate Change Page 25, <http://cdm.unfccc.int/Projects/projsearch.html>.
- Wamukonya, N. 2003. Power sector reform in developing countries: mismatched agendas. *Energy Policy* 31:1273-1289.
- van den Ende, J., K. Mulder, M. Knot, E. Moors, and P. Vergragt. 1998. Traditional and Modern Technology Assessment: Toward a Toolkit. *Technological Forecasting and Social Change* 58:5-21.
- Wang, S., P. Yuan, D. Li, and Y. Jiao. 2011. An overview of ocean renewable energy in China. *Renewable and Sustainable Energy Reviews* 15:91-111.
- Varun, I. K. Bhat, and R. Prakash. 2009. LCA of renewable energy for electricity generation systems—A review. *Renewable and Sustainable Energy Reviews* 13:1067-1073.
- WB. 2008. The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits. World Bank Independent Evaluation Group, Washington DC.
- WEC. 2010. 2010 Survey of Energy Resources. World Energy Council, London.
- Vega, L. A. 2011. Hawaii National Marine Renewable Energy Center.
- Weisser, D. 2004. Power sector reform in small island developing states: what role for renewable energy technologies? *Renewable and Sustainable Energy Reviews* 8:101-127.
- Wilhelmsson, D., T. Malm, R. Thompson, J. Tchou, G. Sarantakos, N. McCormick, S. Luitjens, M. Gullström, J. K. Patterson Edwards, O. Amir, and A. Dubi, editors. 2010. Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy. IUCN, Gland.
- Williams, A. A. and R. Simpson. 2009. Pico hydro - Reducing technical risks for rural electrification. *Renewable Energy* 34:1986-1991.
- VPC. 2008. Productive Uses of Energy. Vattenfall Power Consultant, Maputo.
- Wrisberg, N., A. Helias, U. H. A. de Haes, B. Bilitewski, S. Bringezu, F. Bro-Rasmussen, R. Clift, P. Eder, P. Ekins, R. Frischknecht, and U. Triebswetter. 2002. Part 1: Demand and supply of environmental information. in N. Wrisberg, U. H. A. de Haes, U. Triebswetter, P. Eder, and R. Clift, editors. *Analytical tools for Environmental Design and Management in a Systems Perspective*. Kluwer Academic Publishers, Dordrecht.
- Yamada, N., A. Hoshi, and Y. Ikegami. 2009. Performance simulation of solar-boasted ocean thermal energy conversion plant. *Renewable Energy* 34:1752-1758.
- Zabihian, F. and A. S. Fung. 2011. Review of marine renewable energies: Case study of Iran. *Renewable and Sustainable Energy Reviews* 15:2461-2474.

Renewable Ocean Energy in the Western Indian Ocean

Linus Hammar¹, Jimmy Ehnberg², Alberto Mavume³, Boaventura C. Cuamba³,
Sverker Molander¹

¹ Energy and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden

² Svedpower AB, 401 75 Gothenburg, Sweden

³ Departamento de Física, Universidade Eduardo Mondlane, PO Box 257, Maputo, Mozambique

Abstract

Several African countries in the Western Indian Ocean (WIO) endure insufficiencies in the power sector, including both generation and distribution. One important step towards increasing energy security and availability is to intensify the use of renewable energy sources. The access to cost-efficient hydropower is low in coastal and island regions and combinations of different renewable energy sources will play an increasingly important role. In this study the physical preconditions for renewable ocean energy are investigated, considering the specific context of the WIO countries. Global-level resource assessments and oceanographic literature and data have been compiled in an analysis of the match between technology-specific requirements for ocean energy technologies (wave power, ocean thermal energy conversion (OTEC), tidal barrages, tidal current turbines, and ocean current power) and the physical resources in 13 WIO regions: Kenya, Seychelles, Northern Tanzania and Zanzibar, Southern Tanzania, Comoros and Mayotte, Northern, Central-, and Southern Mozambique, Western-, Eastern-, and Southern Madagascar, Réunion, and Mauritius. The results show high potential for wave power over vast coastal stretches in southern parts of the WIO and high potential for OTEC at specific locations in Mozambique, Comoros, Réunion, and Mauritius. The potential for tidal power and ocean current power is more restricted but may be of interest at some locations. The findings are discussed in relation to currently used electricity sources and the potential for solar photovoltaic and wind power. Temporal variations in resource intensity as well as the differences between small-scale and large-scale applications are considered.

[34] and several potential impacts have been suggested [35]. Still, the magnitude of possible detrimental effects is likely to be limited [36].

2.2. OTEC

OTEC technology utilizes the temperature difference between cold deep water and warm surface water of tropical oceans, which is converted to electricity through heat-exchange principles. The potential of this resource is huge and most pronounced in ocean areas with high temperature differences (ΔT). The highest ΔT s are found in the western Pacific, but adequate ΔT exists in most tropical seas [37]. The power output from OTEC undergoes predictable seasonal variations, associated with the global oceanic circulation.

OTEC technology has been explored for almost a century, but low efficiency and complicated engineering requirements have delayed widespread implementation [28]. Three different OTEC principles have been in focus: open-cycle systems, closed-cycle systems, and hybrid systems. Large intake pipes are used to pump warm water from the surface layer and cold water from the depth. The open-cycle system vaporizes the warm water in low-pressure chambers and leads the steam through large diameter turbines. The cold water is used to re-condense the vapour which can be separated into useful fresh water and saline condensate [12, 38]. The closed-cycle system involves a secondary working fluid which is vaporized, re-condensed, and recycled. Typical working fluids are ammonia or propane. One proposed way of greatly improving the efficiency of OTEC plants is to use solar thermal collectors or sun-heated basins, to boost the temperature of the inflowing surface water before it reaches the heat exchanger [39, 40]. Such solar-boosted OTEC implies some diurnal variation in efficiency and power output.

Commercial-scale OTEC plants will have a capacity of 10–100 MW and will operate either from shore-based facilities, moored platforms, or mobile craft. The shore-based approach implies facilitated logistics and huge power transmission advantages but the number of potential sites becomes limited by the distance between land and deep water; for the cold water intake pipe to be of feasible length the continental shelf must be very narrow. The required ΔT for OTEC to operate adequately is about 20°C [21, 41], but the higher the ΔT , the higher the potential. The surface temperature of tropical oceans is around 25–30°C and it is generally assumed that cold enough water is found at 1000 m depth (however, in certain areas it may be found less deep). For land-based systems cold water must be found within accessible distance from shore. A maximum distance of 25 km from land has often been used

as an initial localization criterion [12, 21, 42], but pipe length is an important economic factor, and shorter distances are much preferable. Based on [43, 44] distances of 5 and 10 km from shore to a ΔT of 20°C were applied as the criteria for high and conditional potential, respectively (only land-based OTEC was considered).

Other physical criteria for OTEC are related to slope, bottom substrate, allowing safe mooring, and ocean currents that must cater for an efficient removal of discharge water since all OTEC systems imply large quantities of discharge water with altered temperatures that may influence surrounding ecosystems.

2.3. Tidal barrages

Tidal barrages utilize the potential energy of tidal elevations. The gravitational forces of the moon, the sun, and the centrifugal forces of the rotation of Earth, affect the oceans and give rise to global tidal waves. The tidal waves follow a predictable pattern where the tide rises (flood) and falls (ebb) once (diurnal tides) or twice per day (semidiurnal tides). In addition, the magnitude of tidal waves is increased twice per month, resulting in stronger spring tides and weaker neap tides. To a lesser degree, weather conditions also affect the magnitude of tides. Although the tidal range is low in the open ocean it can be greatly amplified by the position of landmasses and ocean bathymetry such as gently rising slopes [45].

As tides are highly predictable the power output from tidal power can be determined in advance with only small weather-induced deviations. Nevertheless, the hourly and weekly variation, with periods that are not in tune with human consumption patterns, is a drawback for tidal power.

The principle of tidal barrages is to trap a fraction of the tide and keep it out of phase with the natural tide, hereby creating a difference in water level (head) between the enclosed water and the sea. The water levels are allowed to even out by passing through low head turbines. Power can be generated during ebb (one-way operation) or during both ebb and flood (two-way operation) [46]. In the case of one-way operation the basin is filled up through open gates during flood and water is let out through turbines when the receding ebb has created a sufficient head (H_{min}). Two-way operation means that water is directed through turbines both during flood and ebb, and more power can be generated. By power plant design (e.g. adjustment of H_{min} and flow rate) a tidal barrage can be optimized with respect either to power output or to power availability over time, the latter of particular importance in small electric grids.

resource-based potential were used to categorize results: *high* (physical conditions clearly meeting or exceeding the general requirements for the technology) and *conditional* (physical conditions at the lower end of general requirements). The applied criteria are compiled in Table 1.

Most RES imply more or less intermittent power generation, and the nature of these variations influences the quality of the resource. The ocean energy sources considered in this study have temporal variations ranging from hourly to seasonal. The predictability of these variations – that is, the certainty in forecasting energy availability over time – was ranked into *low* (not predictable from one day to the next), *moderate* (essentially predictable over days), or *high* (essentially predictable over years).

Table 1. Summary of temporal variability, predictability, and applied criteria for categorizing the resource-based potential. The criteria refer to annual means if not specified otherwise.

	Wave power	OTEC	Tidal barrages	Tidal current turbines	Ocean power	Solar PV	Wind power
Temporal variability	Daily & seasonal	Seasonal	Hourly & weekly	Hourly & weekly	Seasonal	Hourly & seasonal	Hourly & seasonal
Predictability	Moderate	High	High	High	High	Moderate	Low
Ranking criteria	$\geq 25 \text{ kW m}^{-1}$	$\geq 20 \text{ AT}$	$\geq 5 \text{ m}$	$\geq 2 \text{ m s}^{-1}$	$\geq 1.5 \text{ m s}^{-1}$	$\geq 5.5 \text{ kWh m}^{-2} \text{ d}^{-1}$	$\geq 5.5 \text{ m s}^{-1}$
	$\leq 5 \text{ km}$	mean tidal	peak speed	seasonal average speed	$3-5.5 \text{ kWh m}^{-2} \text{ d}^{-1}$	$4-5.5 \text{ m s}^{-1}$	
	$\geq 20 \text{ AT}$	range	peak speed	seasonal average speed			
	$\leq 10 \text{ km}$	mean tidal	peak speed	seasonal average speed			
	$\leq 25 \text{ kW m}^{-1}$	range	peak speed	seasonal average speed			
Conditional	$15-25 \text{ kW m}^{-1}$	$\geq 20 \text{ AT}$	$2.4-5 \text{ m}$	$\geq 1.5 \text{ m s}^{-1}$	$1-1.5 \text{ m s}^{-1}$	$3-5.5 \text{ kWh m}^{-2} \text{ d}^{-1}$	$4-5.5 \text{ m s}^{-1}$

Wave power devices convert energy from wind driven surface waves to electricity. As the energy in waves dissipates slowly it can be carried over long distances and reach shores far beyond its origin. The global distribution of wave power reflects the wind patterns, with most

2.1. Wave power

energy bound to western-facing coasts at high latitudes and eastern-facing shores at low latitudes [28]. As the energy originates from wind, the wave power resource is variable and undergoes both seasonal and daily changes. However, swell (long wavelength waves), which characterize wave patterns at low latitudes, even out much of the short-term variation. Wave power is more predictable and less variable than wind power [28].

Wave power is extracted by using the motion of water to spin turbines or drag linear generators. Currently, more than 80 different technical concepts are under development [17]. Some devices are made to operate as floating arrays in deeper coastal water; others will be moored to the bottom in the shallows, or installed as wave breakers on the shore. While shore-based wave power plants are large, floating devices consists of small units (20–1000 kW). As the frequency spectra of waves differs between sites, the bandwidth of a device can be regulated to tune it to particular waves or to keep efficiency adequate over a wider range of wave conditions [29]. The latter, generalist, approach may be advantageous in small-scale applications where less site-specific background information is available.

Most projected installations of wave power concern large arrays with hundreds or thousands of units, but being based on small units several devices may also be suitable for small-scale deployment. Interesting examples of small-scale options are the Cape Verde device developed by Euro Wave Energy [10] and the SAS-2 converter presented by [30]. Both of these converters have shore-based generators, a robust design, and are promoted for developing countries, including remote community electrification and the production of potable water (desalination).

At the basic level, wave power potential is measured in terms of energy density per wave crest (kW m^{-1}). Current technologies harvest about one fifth of the available resource, but numbers differ between conditions and devices. Since the required energy density varies between devices it is not straightforward to determine generic resource criteria for wave power potential. Based on [17], wave power devices are typically optimized for 15–35 kW m^{-1} , and 20 kW m^{-1} has been regarded an good potential [31].

In this study the criterion for high potential was set to 25 kW m^{-1} deep water wave crest while the criterion for conditional potential was set to 15 kW m^{-1} . It should be noted also that low levels of energy density may become economic as long as the utility factor is high [32]. Furthermore, the occurrence of extreme waves must be considered [33] as wave power systems are relatively fragile and few floating devices would stand the harsh conditions of a tropical cyclone, which are known to cause extensive damage on exposed floating devices during their passage. The knowledge on environmental impacts from wave power is scarce

Earth's rotation and are strongest in western parts of the oceans. Although the mass transport of oceanic currents is immense, the power density is generally low due to low velocities. One of the most powerful ocean current systems in the world is the Somali-Agulhas system which stretches along the East African coast [28].

Over the past fifty years, there have been numerous innovations suggested for the extraction of energy from the large ocean currents. In order to make use of slow currents, the actual flow over the rotor has to be enhanced. This problem has been approached by various designs where the most common has been to construct a ducted shroud over the turbine. The water is dragged through the turbine due to the pressure gradient that develops from the shape of the duct, increasing the flow velocity and improving the conversion efficiency of the device. Previous innovations for ocean current power has been of huge dimensions (with units measuring up to 150 m in diameter [28]). A recent approach, which is based on 220–500 kW units measuring 12 m in diameter, is the Deep Green prototype [64]. In this concept the turbine is mounted on an anchored submerged kite that circulates with the current and amplifies the experienced water speed over the rotor by a factor of ten, according to the developer. The Deep Green targets current velocities from 1 m s^{-1} which means that the number of potential sites increases in comparison to other ocean current power technologies. Another ocean current power technology under development is the Florida Hydro which measures 45 m in diameter and produces 2–3 MW per unit [65]. Regardless of the technology used, only large-scale projects are likely to be commissioned since ocean currents are associated with rough offshore conditions and expensive power transmission.

In this study, the criteria for high and conditional potential for ocean current power were set to seasonal average coastal current speeds of 1.5 and 1 m s^{-1} , respectively. However, as the technology has not been tested at full scale any assessment is associated with high uncertainties.

2.6. Land-based RES

Insolation and wind energy are examples of RES that can complement ocean energy although coastal cloudiness may reduce the insolation and coastal wind is not as prominent in the tropics as in high latitudes, due to low difference between land and sea temperature. The technical development of solar photovoltaic (PV) and wind power is far beyond that of ocean energy and the resource distribution is well known at a coarse level. This study examines how coastal solar and wind resources match with ocean energy. Tanzanian energy tariffs [26, 27]

for electricity sold to main-grid and off-grid systems (including feed-in tariffs based on diesel costs) were the basis for approximated resource criteria. The criteria for high and conditional potential for solar PV were set to insolation levels of $5.5 \text{ kWh m}^{-2} \text{ d}^{-1}$ and $3 \text{ kWh m}^{-2} \text{ d}^{-1}$. For wind power, average speeds of 5.5 m s^{-1} and 4 m s^{-1} (at 10 m height) were used.

3. Methods

The resource-based potential and other physical preconditions for each technology in each studied region were assembled from oceanographic literature, databases, and global-level resource assessments. Some of the data were compiled in a previous thesis [66].

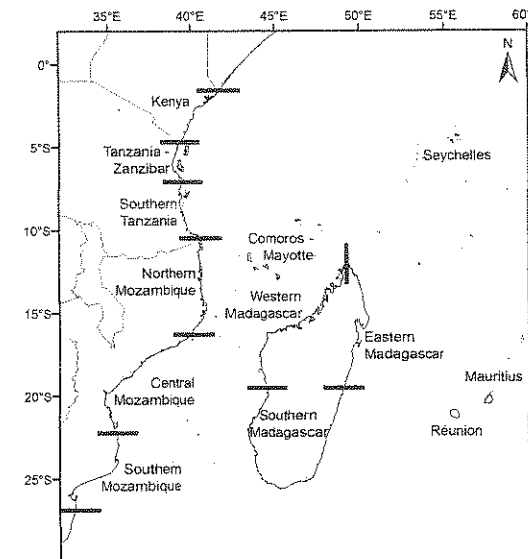


Figure 1. Map showing the investigated part of the Western Indian Ocean and the 13 assessed regions (indicated by their name).

Table 2. Key geophysical conditions [68] and landfall periodicity of tropical cyclones based on the period 1980–2009 [69]. Cyclone periodicity refers to the average number of years between cyclones that reach the coast of each region; it is not a measure on cyclone frequency at a given location. Oceanic currents are labelled as EACC (East African coastal current), SEC (south equatorial current), ECC (equatorial counter current), Moc (Mozambique current), and Mac (Madagascar current).

Region	Typical coastal morphology	Shelf bathymetry	Dominant ocean current	Landfall periodicity of cyclones (years)
Kenya	Limestone rock	Variable	EACC	-
Seychelles	Limestone, granite	Variable	ECC	20
Tanzania-Zanzibar	Limestone	Variable	EACC	-
Southern Tanzania	Limestone	Narrow shelf	EACC	30
Comoros and Mayotte	Volcanic rock	Narrow shelf	Moc	3
Northern Mozambique	Limestone	Narrow shelf	Moc	3
Central Mozambique	Estuarine and sand	Shallow	Moc	2
Southern Mozambique	Sand	Shallow	Moc	10
Western Madagascar	Estuarine and rock	Variable	Moc	1
Eastern Madagascar	Sand and rock	Narrow shelf	SEC	1
Southern Madagascar	Sand and rock	Narrow shelf	Mac	1
Réunion	Volcanic rock	Narrow shelf	-	1.5
Mauritius	Volcanic rock	Narrow shelf	-	2

The WIO case-study is defined by Fig. 1, based on [67]. The WIO was separated into 13 regions in order to facilitate the analysis of results: Kenya, Seychelles, Tanzania–Zanzibar, Southern Tanzania, Comoros and Mayotte, Northern Mozambique, Central Mozambique, Southern Mozambique, Western Madagascar, Eastern Madagascar, Southern Madagascar, Réunion, and Mauritius. The WIO has a tropical to sub-tropical climate with water surface temperatures between 20 and 30°C and air temperatures rarely falling below 20°C. The climate is strongly affected by monsoons, where the northern monsoon generates light steady winds of 5 m s⁻¹ from November to March and the southern monsoon generates stronger winds (up to averages of 9 m s⁻¹ in southern parts of the region) from June to September [68]. The monsoon wind patterns influence the seasonal configuration of waves and ocean currents. In this study,

Southern WIO experiences recurrent tropical cyclones with powerful and potentially devastating impacts on coastal areas. Tropical cyclones appear during the northern monsoon with peak occurrence in January–March, most frequently exposing Madagascar, Réunion and Mauritius, Mozambique, and the Comoros [69]. The geological history of the WIO originates from the break-up of Gondwanaland including Madagascar's drift with respect to continental Africa, the formation of the Indian Ocean marginal basins [70]. A steep continental shelf was formed. Coastal features are typically dominated by Pre-Cambrian rock, volcanic rock, fossil coral limestone, and estuarine coastal plains [68]. These geophysical conditions, compiled in Table 2, are important for the feasibility of different technologies.

3.2. Wave power

The energy flux P in surface waves can be calculated from the wave height and the wave period according to Eq. 1:

$$P = \frac{\rho g^2}{64\pi} H^2 T \quad (1)$$

where ρ is the water density (kg m⁻³), H is the significant wave height (m), and T is the wave period (s). The unit is kW m⁻¹ that represents the power per metre of wave crest. The expression is restricted to surface waves in water deeper than half the wavelength.

The first screenings of wave power resources relied on visual observations from maritime reports. Obviously, the method is rather qualitative but has been defended by the assumption that visual observations generally tend to underestimate rather than overestimate the significant wave height [71]. Modern methods are based on altimetry, with height and period of waves determined from remote-sensing observations and calibrations using buoy measurements. Two drawbacks of remote sensing methods are inaccuracy in near-shore waters [72, 73] and difficulties in fully accounting for the energy in ocean swell [72].

In this study, global-level wave power assessments generated from visual observations [71] and altimetry-based models [33] were used. Quayle and Changlier [71] calculated annual means of wave power from an extensive global database of marine vessels reports from 1971–

81, calibrated by a wave climate database. Barstow et al. [33] presented annual and seasonal means of wave power, and the outcome of extreme waves, based on ten years of altimetry data calibrated by buoy measurements. A comparison of the two data sources showed that the altimetry data [33] with higher spatial and temporal resolution generated the more conservative estimates for WIO coast. This source was hence used as the primary source. For illustration purposes (Fig. 2), inverse distance weighted interpolation (IDW), based on two neighbouring values and a spatial resolution of one degree, was performed in ArcGIS to generate data for each intersection of the coast. As data were based on deep-water conditions the actual wave power at the shore will be reduced [73]. Based on [74] this reduction of wave power would be <10%. However, site-specific investigations are needed for detailed resource assessments.

3.3. OTEC

Several studies have addressed the global level resource potential for OTEC based on the ΔT and bathymetry [28, 37, 38, 41]. None of these studies have provided detailed descriptions of the OTEC potential in the WIO, so bathymetry and temperature data acquired from the African Marine Atlas [75] were used to examine the OTEC-related conditions in the WIO: shoreline contour [76], 1000 m depth contour [77], and ocean temperatures [78], for each increment of the coast. The distance from shore to 1000 m depth was calculated in ArcGIS. The annual means of ΔT were extracted for all coastal locations found within 10 km distance from the 1000 m depth. Global-level maps of ΔT for February and August [79] were used for an overview of seasonal variations.

3.4. Tidal barrages

The tidal range at WIO locations was compiled from oceanographic literature [80-84]. To assess the potential at criteria-meeting locations, the power output (per km²) was calculated for different barrage designs. A basic semidiurnal tidal model (Eq. 2), based on a daily period of 12 h 25 min and a monthly period of 14.75 days [54], was used to calculate the tidal fluctuations at each location:

$$Z = SR \cos\left(2\pi \frac{t}{T_1}\right) \left[A - B \cos\left(2\pi \frac{(t+T_2)}{T_2}\right) \right] \quad (2)$$

$$A = 1 - \frac{(SR-NR)}{(2SR)}$$

$$B = \frac{(SR-NR)}{(2SR)}$$

where Z is the tidal level, SR is the spring range (average range during peak spring), NR is the neap range (average range during full neap), T_1 is the daily period and T_2 is the monthly period.

The tidal model (Eq. 2) was calibrated for each criteria-meeting location and SR and NR were estimated from tidal tables (March–June 2010) [83]. No corresponding data were available for the Nosy Chesterfield location (Madagascar), instead SR and NR were estimated on the basis of locations with equivalent mean tidal range: Moçimboa da Praia and Quelimane (Mozambique).

Eq. 3 describes the electric energy E_e of a tidal barrage:

$$E_e = c_p \frac{\rho g A H^2}{2} \quad H \geq H_{min} \quad (3)$$

where c_p is the conversion efficiency, ρ is the density of sea water (kg m⁻³), g is the gravitational force (m s⁻²), A is the intake area of turbines (m²), H is the difference (m) between the water levels inside and outside the basin. Eq. 2 and 3 were combined to calculate the potential power output and power availability over time for tidal barrages using (i) one-way operation mode, and (ii) two-way operation mode. H_{min} and the flow rate through turbines were optimized for maximum power output [46]. Power output was calculated in MATLAB[®] assuming a conversion efficiency of 0.75 and a constant basin depth.

3.5. Tidal current turbines

To the knowledge of the authors there has been no large-scale modelling of tidal currents in the WIO. However, site-specific information of tidal current velocities at various locations was compiled from literature [9, 81, 85-88] and unpublished data [89]. Where observations specifically referred to surface or bottom currents the mid-water current speed was calculated using the 10th power law for turbulent flow [90].

Quantitative estimates of the theoretical resource were not achievable due to a lack of site-specific information on bathymetry and exact positioning of measurements. Instead, the

potential power output was calculated for specific tidal current turbines, located at the criteria-meeting locations. Most of the compiled data were restricted to measurements or estimations of maximum speed. Therefore, a semi-diurnal tidal current model (Eq. 4) was used to simulate the full tidal cycle. The model was modified from [60] by adding the ratio of ebb to flood currents (d_f):

$$v = \begin{cases} \left[MSS + MNS \cos\left(\frac{T_2}{2m}\right) \cos\left(\frac{T_1}{2m}\right) \right] & nT_2 \leq t \leq \frac{2}{(2n+1)T_2} \\ -d_f \left[\left[MSS + MNS \cos\left(\frac{T_2}{2m}\right) \cos\left(\frac{T_1}{2m}\right) \right] \right] & \frac{2}{(2n+1)T_2} < t < \frac{2}{(n+1)T_2} \end{cases} \quad n = 1, 2, 3, \dots \quad (4)$$

where MSS is the maximum speed during peak spring and MNS is the maximum speed during full neap given as a proportion of MSS , t is time, T_1 is the period of the daily tidal cycle, and T_2 is the period of the monthly tidal cycle. Based on [18] and [62], the maximum speed from the different locations was assumed to represent MSS while the MNS was set to 0.6. The d_f was set to 0.84 based on analysis of Mozambican tidal current data described in [86].

Eq. 5 describes the generated power P_g for a tidal current turbine:

$$P_g = 0.5 C_p \rho A v^3 \quad v \geq v_{cut-in} \quad (5)$$

where C_p is the turbine conversion efficiency (here assumed as 0.4 [90]), ρ is the density of sea water (kg m^{-3}), and A is the area swept by the rotor (m^2). Power output was calculated for three different size-classes of tidal current turbines: (A) a large device based on the SeaGen turbine employed in the UK since 2008 [17]; (B) a small device based on the Verdant free flow kinetic hydropower system employed in the New York City's East River since 2006 [17, 18]; and (C) a hypothetical micro-scale device corresponding to an anchored raft deployed with four Gorlov helical turbines.

Applied technical assumptions: (A) 1.2 MW rated power in 2.4 m s^{-1} current, 0.7 m s^{-1} cut-in speed, 400 m^2 swept rotor area, 30 m target depth; (B) 36 kW rated power in 2.1 m s^{-1} current, 0.7 m s^{-1} cut-in speed, 20 m^2 swept rotor area, $6-20 \text{ m}$ target depth; (C) 20 kW rated power in 2 m s^{-1} current, 0.5 m s^{-1} cut-in speed, 10 m^2 swept rotor area, 5 m minimum depth.

3.6. Ocean current power

The WIO is well covered in oceanographic literature and the oceanic currents have been investigated by various methods. Still, there are no detailed mappings of coastal surface current velocities. Areas of particularly strong coastal currents were identified from [91] and [92], and were further investigated through a comprehensive set of historical ship drift data. These ship drift observations, originally obtained from the Meteorological Office of Historical Surface Currents, consist of non-filtered reports from 1854 to 1974 which were compiled by Cutler and Swallow [93] into means of determining current velocity with a geographical resolution of one degree (1°) quadrangles, and a temporal resolution of 36 periods from January to December (10-day means). Outliers (where both flow direction and speed strongly deviated from the prevailing current) were removed, and mean and maximum values were calculated for northern and southern monsoon periods. Finally, the data were interpolated (IDW) in ArcGIS for illustration purposes (Fig. 3).

Although there are obvious uncertainties associated with the use of historical ship drift data the influence from wind and navigation errors has been shown to be small in strong currents and can be neglected when large data sets are used [94].

3.7. Current electricity supply and land-based RES

Information on currently used power sources was compiled from country-specific reports [1, 13, 95-99]. In order to put the ocean energy resources in the context of future energy systems, basic satellite generated data of insolation and wind speed were derived from the Atmospheric Science Data Center [100].

4 Results and Discussion

4.1. Wave power in the WIO

High potential for wave power ($\geq 25 \text{ kW m}^{-1}$) was found throughout southern WIO, including Southern Mozambique, Southern Madagascar, Réunion, Mauritius, and parts of Eastern Madagascar. The wave power is highest in Southern Madagascar where the annual average reaches 50 kW m^{-1} (Fig. 2, Table 3). Most of Eastern Madagascar and a few islands of the Seychelles have a wave power potential rated as conditional ($15-25 \text{ kW m}^{-1}$). The seasonal variation of wave power (the ratio of minimum individual monthly wave power to the annual

average) is low in the southern hemisphere and throughout the WIO [33]. Still, there are differences between seasons, and the wave power is higher during the southern monsoon (southern hemisphere winter). During this period the wave power exceeds 15 kW m^{-1} in most of the WIO. Furthermore, analyses by Cornett [73] and Barstow et al. [33] showed that the frequency of destructive waves is low throughout most of the WIO (estimated as the ratio of the highest significant wave height to the average wave height).

There is no doubt that wave power resources allow for considerable energy extraction in the WIO, and if wave power technology becomes available, the resource may be of interest both for large-scale generation and for micro-scale applications for remote area electrification and desalination purposes. However, the occurrence of tropical cyclones in southern WIO is likely to restrict the number of suitable sites.

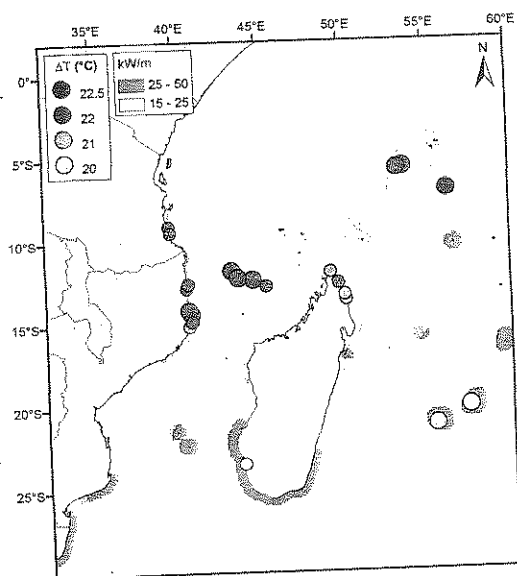


Figure 2. Distribution of wave power and OTEC resources in the WIO. Green areas indicate annual mean wave power (kW m^{-1}) for coastal deep-water conditions. Circles mark locations with $\Delta T \geq 20^\circ\text{C}$ within 5 km (large circles) and 10 km (small circles) from shore. Isoclines indicate 1000 m depth.

Table 3. Deep-water wave power (kW m^{-1}) for selected coastal locations in the WIO, based on visual observations [71] and altimetry-based models [33].

Region	Location	Visual observations	Altimetry-based modeling		
		Annual	Annual	January	July
Kenya	Kiunga	16	10-15	5-10	20-30
Seychelles	Seychelles	-	10-15	5-10	20-30
Seychelles	Coetivy Island	-	15-20	5-10	30-40
Tanzania Zanzibar	Zanzibar	12	5-10	<5	15-20
Southern Tanzania	Lindi	14	5-10	<5	10-15
Comoros and Mayotte	Comoros and Mayotte	12	5-10	5-10	10-15
Northern Mozambique	Nacala	14	10-15	5-10	15-20
Northern Mozambique	Quirimbas Archipelago	12	<5	5-10	10-15
Central Mozambique	Beira	27	10-15	<5	10-15
Central Mozambique	Quelimane	19	10-15	5-10	15-20
Southern Mozambique	Inhambane	34	20-30	15-20	30-40
Eastern Madagascar	Cape East	-	15-20	10-15	30-40
Western Madagascar	North-West coast	10	<5	5-10	<5
Southern Madagascar	Tolagnaro	-	40-60	30-40	40-60
Southern Madagascar	Androka	38	30-40	20-30	40-60
Southern Madagascar	Fenoambany	-	20-30	20-30	40-60
Southern Madagascar	Andavadoaka	18	20-30	10-15	30-40
Réunion	Réunion	-	20-30	15-20	30-40
Mauritius	Mauritius	-	30-40	20-30	40-60
Mauritius	Agalega	-	20-30	10-15	30-40

4.2. OTEC in the WIO

High potential for OTEC was indicated at 11 locations in the Seychelles, Northern Mozambique, the Comoros, Réunion, and Mauritius (Fig. 2, Table 4). Conditional OTEC potential was found in Southern Tanzania, and Eastern and Southern Madagascar. The locations with highest OTEC potential were the Comoros, Mozambican Nacala, and several islands in the Seychelles. According to the analysis, the ΔT averaged 22°C within 3 km from the coast at these locations. The results are supported by the temperature measurements presented by Chapman [101] but has not been recognized in global-level assessments of OTEC potential [12, 28, 38]. Because of strong deep-sea currents, the seasonal variations of ΔT are relatively high in the WIO compared to other oceans [37]. Even at the most suitable locations ΔT dips to $19\text{--}20^\circ\text{C}$ during the Southern monsoon.

OTEC, particularly solar-boosted systems, may be a suitable power source for several regions of the WIO once the technology is fully developed, given the particular values of low variation and predictability of power generation from this energy source, which is indicated by the current OTEC ambitions in Réunion [12, 13]. It should be noted though, that the environmental impacts of OTEC are not fully known [102].

Table 4. Minimum distance between shore and 1000 m depth and annual mean temperature difference between surface water and deep water at 1000 m depth for locations in the WIO.

Region	Location	Distance (km)	ΔT (°C)
Seychelles	Desroches Island	2.5	22
Seychelles	Poivre Island	2.5	22
Seychelles	Coetivy Island	3	22.5
Southern Tanzania	Kilwa	7.5	22
Southern Tanzania	Lindi	9.3	22
Comoros and Mayotte	Grande Comore	2.1	22
Comoros and Mayotte	Anjouan	2.3	22
Comoros and Mayotte	Moheili	4.9	22
Comoros and Mayotte	Mayotte	5.7	22
Northern Mozambique	Nacala	2.8	22
Northern Mozambique	Memba	3.5	22
Northern Mozambique	Calajulo	5	21
Northern Mozambique	Matibane	5.7	22
Northern Mozambique	Pemba	7.6	22
Northern Mozambique	Quissima Island	8	22
Eastern Madagascar	Andranovondronima	6	21
Eastern Madagascar	Masendrono	8.2	21
Eastern Madagascar	Ampondrabe	8.7	22
Eastern Madagascar	Vohémar	9.3	21
Southern Madagascar	St Augustin	8.4	20
Réunion	Réunion	1.8	20.5
Mauritius	Mauritius	1.3	20

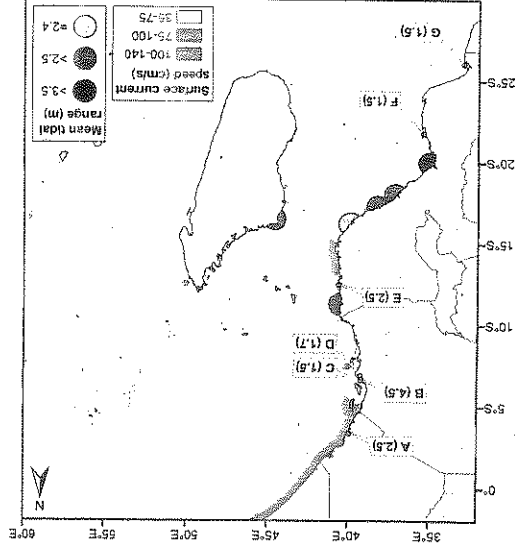


Figure 3. Indications of tidal and ocean current resources in the WIO. Circles show mean tidal range at selected locations (mean tide ≥ 2.4 m). Labels indicate sites with tidal currents ≥ 1.5 m s⁻¹ (mid-water maximum speed indicated, in s⁻¹) at locations: A – Watamu, B – Kunduchi, C – Mbudya, D – Dar es Salaam harbour, E – Montepuez Bay, F – Bazaruto Island, G – Inhaca Island. Green areas indicate seasonal average surface speed (cm s⁻¹) of ocean currents, based on ship drift. Light grey isoclines indicate 1000 m depth.

4.3. Tidal barrages in the WIO

Because of the location of Madagascar, the oceanic tidal wave induces elevated tides over the East Africa continental coast and Western Madagascar (Fig. 3). The semidiurnal tides of Mozambique, Tanzania, Kenya, Comoros and Mayotte and Western Madagascar are classified as macro-tidal, defined by a spring tidal range above 3 m [82], and several locations have tides comparable to other areas where small-scale tidal barrages are operating or planned (China, Russia, India). However, the mean tide does not reach 5 m at any location and thus the potential for tidal barrages has only been ranked as conditional (Central and Northern Mozambique and Western Madagascar). The inner parts of the Sofala Bank in Central

Mozambique (Beira), where mean tidal range exceeds 3.5 m, offers a potential of ~10 GWh $\text{km}^{-2} \text{y}^{-1}$ (Table 5). But, considering the coastal morphology, this area may not be suitable for the construction of barrages. The limestone rock formations of the northern Mozambique–Tanzanian coast provide more suitable conditions for barrages, but potential environmental effects of modifying tidal regimes in sensitive environments may restrict possible developments to micro-scale barrages. The low temporal availability of power (Table 5) impedes the usefulness of tidal barrages in decentralized grids.

Table 5. Mean tidal range, annual power output, and temporal availability power (% of time) for locations in the WIO with a mean tidal range above 2.4 m. Calculations are based on optimization in respect to power output, at the cost of temporal availability.

Region	Location	Mean range m	One-way operation		Two-way operation	
			MWh km^{-2}	%	MWh km^{-2}	%
Central Mozambique	Beira	3.58	6278	32	10 358	44
Central Mozambique	Quelimane	2.60	2809	30	4919	33
Central Mozambique	Pebane	2.52	2777	30	4858	33
Central Mozambique	Angoche	2.40	2895	30	5060	33
Northern Mozambique	Moçimboa da Praia	2.60	2885	31	5055	36
Western Madagascar	Nosy Chesterfield	2.60	2862	30	5004	33

4.4. Tidal current turbines in the WIO

Only three locations with high potential ($\text{MSS} \geq 2 \text{ m s}^{-1}$) for tidal current turbines were identified, and out of these only two were supported by quantitative data (Tanzania–Zanzibar and Kenya) (Fig. 3). Strong tidal currents have also been reported, but not verified, at Pemba Island (Zanzibar). Another four locations with conditional potential for tidal current turbines were found along the Mozambican and Tanzanian coasts. The amount of power that can be generated by tidal current turbines of different sizes, at each of the identified sites, is given in Table 6. Based on available data, the potential for tidal current turbines in the WIO seems limited, but unrevealed locations with strong currents may exist.

Table 6. Maximum spring speed (MSR), site depth, quality of data (M = measurements, Q = qualitative observations), potential annual power output, and power availability as percentage of time for tidal current turbines at locations in the WIO with tidal currents $\geq 1.5 \text{ m s}^{-1}$. Power output is calculated per one (1) device of specific dimensions corresponding to large, small, and micro tidal current turbines.

Region	Location	MSS m s^{-1}	Depth m	Quality	Large		Small		Micro	
					MWh	%	MWh	%	MWh	%
Kenya	Watamu	2.5	6	M	–	–	148	74	78	82
Tanzania–Zanzibar	Kunduchi	4.5	–	M	–	–	–	–	128	90
Tanzania–Zanzibar	Mbonya	1.5	15	M	–	–	42	53	22	69
Tanzania–Zanzibar	Dar es Salaam	1.7	7	U	–	–	64	60	34	73
Northern Mozambique	Montepuez Bay	2.5	50	Q	3 728	74	–	–	–	–
Central Mozambique	Bazaruto Island	1.5	23	M	–	–	42	53	22	69
Southern Mozambique	Inhaca Island	1.5	10	M	–	–	42	53	22	69

4.5. Ocean current power in the WIO

The most fast-flowing ocean currents that pass through the WIO are the Somali Current and the East African Current, which are strongest during the southern monsoon, and the Mozambique Current which is strongest during the northern monsoon. During the southern monsoon, current speeds have been reported to reach extreme 3.5 m s^{-1} off the Somali coast [103], and to average 2 m s^{-1} at Zanzibar [104]. More restrictively, the historical ship drift from Cutler and Swallow [93] rendered mean / maximum speeds of $1.2 / 1.9 \text{ m s}^{-1}$ for the Kenyan coast, and $0.7 / 1.5 \text{ m s}^{-1}$ for Tanzania–Zanzibar, respectively (Fig. 3, Table 7). Further, mean speed mean speeds of $1–1.5 \text{ m s}^{-1}$ and maximum speeds above 2 m s^{-1} have been reported for the northern coast of Mozambique [91]. Here, the historical ship drift indicated northern monsoon mean / maximum speeds of $0.9 / 1.4 \text{ m s}^{-1}$.

On the basis of these results, Kenya (northern latitudes) and Northern Mozambique (southern latitudes) may have at least conditional potential for ocean current power. The continental shelf is very narrow in both areas which indicates that the strong currents sweep close to shore, which is necessary for power extraction. Hitherto, the ocean current power technologies are in early development stages; as a brief indication though, a small ocean current power device would generate approximately 160 and 370 MWh per unit and month in continuous currents of 1.4 and 1.6 m s^{-1} , respectively. However, the possible environmental impacts are not known.

Table 7. Coastal surface current speed (m s^{-1}) based on ship drift records in regions of WIO. For ship drift data [93], mean speed has been calculated as the mean of all reporting during November–April and May–October (1854–1974), for northern and southern monsoons respectively. Maximum speed is based on year-averaged 10-day periods.

Region	Northern monsoon		Southern monsoon	
	Mean	Max	Mean	Max
Kenya	0.7	1.5	1.2	1.9
Tanzania-Zanzibar	0.7	1.5	0.7	1.4
Southern Tanzania	0.4	0.7	0.8	1.3
Northern Mozambique	0.9	1.4	0.6	1.1
Eastern Madagascar	0.5	1.2	0.8	1.4
Southern Madagascar	0.7	1.1	0.6	1.3
Djibouti [90]				
Northern Mozambique	1–1.5			>2

4.6. Outlook: ocean energy in the Western Indian Ocean

A summary of the results for each WIO region is given in Table 8, showing that there is a substantial resource-based potential for ocean energy in the WIO. Some examples of how the ocean energy potential matches with current energy supply and solar and wind resources are discussed below.

About half of the small population of the Comoros currently have access to electricity. About 90% of the ~5 MW capacity is generated from imported fossil fuel [5, 96]. The resource potential for OTEC is rated high, with several locations where sufficient ΔT is available close to shore. A single small-sized OTEC plant of 10 MW would cover several times the current power consumption of 20 GWh y^{-1} . The insolation is also high and could be utilized for boosting the capacity of OTEC. While OTEC and insolation both peak during the northern monsoon, the wind power potential peaks during the southern monsoon (wind speed means above 5.5 m s^{-1}). The situation is comparable at the nearby Mayotte (France) where the economic situation may allow for taking a lead on development. However, the relatively high occurrence of tropical cyclones in this region is an important factor which may discourage the use of exposed devices.

The remote islands of Réunion and Mauritius have already shown particular interest in exploring the opportunities of ocean energy [13]. The electric grids have full coverage, and

new power sources are needed to substitute the substantial fossil fuel imports [13, 99]. Both Réunion and Mauritius have high resource-based potentials for wave power, wind power, OTEC, and solar power. The former two peak during the southern monsoon while the latter two peak during the northern monsoon, which represents a prolific combination. The risk of devastating tropical cyclones may put emphasis on more robust technologies such as land-based OTEC.

The population of the Seychelles is small and scattered over a multitude of remote islands. The electrification level is near 100% but the total dependence on fossil fuel, with extraordinary annual oil imports of 30 barrels per capita, may be a strong incentive for increased use of RES [5, 95]. The potential for solar PV is high year round. The potentials for wind and wave power were ranked as conditional on an annual basis, but are high during the northern monsoon. Under the particular circumstances of fossil fuel dependence, all three energy sources are likely to become useful for future energy supply in the Seychelles. Wind power has the advantage of being a well-proven technology and is more easily maintained than wave power. The low temporal variability and higher predictability of wave power, improved by the oceanic-swell-dominated conditions in the Seychelles, may come to motivate the use of this technology at particular locations. By contrast, the high potential for OTEC in the Seychelles is not likely to be of interest due to the small populations on the islands.

In Madagascar, the energy sector is undeveloped with only about 10–15% [3] of the rural population having access to electricity. However, Madagascar also has huge unexploited resources of hydropower and recent findings of fossil fuel [97]. The high resource potential for wave power and solar PV may consequently be of low interest, but of possible use for remote area electrification/desalination purposes. Tropical cyclones pose a potential hindrance throughout Madagascar's coast, not least for wave power.

Mozambique has an extremely low electrification level (2–3% in rural areas [3]), but has a good supply of inexpensive hydropower to the national electric grid [98]. The high resource-based potential for wave power in southern parts of the country may possibly be of interest for remote area electrification. The wind power potential is fairly low in coastal areas of Mozambique, but solar PV may be a good complement.

Table 8. Summary of results as the highest rank of resource-based potential for ocean energy, solar PV, and wind power for each region. H indicates 'high' resource potential and C indicates 'conditional' resource potential (see Table 1). Note that ranks may be based on single sites, not necessarily representative for the whole region. All ranking is based on annual averages; peak seasons are indicated in brackets where (S) is southern monsoon (Nov–Apr) and (N) is northern monsoon (May–Oct). Empty cells (–) indicate low potential. The current supply of power is indicated. WP = wave power, OTEC = ocean thermal energy conversion, TB = tidal barrages, TCT = tidal current turbines, OCP = ocean current power.

Region	WP	OTEC	TB	TCT	OCP	Solar PV	Wind power	Current supply
Kenya	–	–	–	H	C (S)	C (N)	C (S)	Hydro, oil, RES
Seychelles	C (S)	H (N)	–	–	–	H (N)	C (S)	Oil
Tanzania-Zanzibar	–	–	–	H	–	H (N)	C (S)	Hydro, coal, gas, oil
Southern Tanzania	–	C (N)	–	–	–	C (N)	C (S)	Hydro, coal, gas, oil
Comoros and Mayotte	–	H (N)	–	–	–	H (N)	C (S)	Oil
Northern Mozambique	–	H (N)	C	H	C (N)	C (N)	C (S)	Hydro, coal, oil
Central Mozambique	–	–	C	C	–	H (N)	C	Hydro, coal, gas, oil
Southern Mozambique	H (S)	–	–	C	–	C (N)	C	Hydro, coal, oil
Western Madagascar	H (S)	–	C	–	–	H	C (S)	Hydro, coal, oil
Eastern Madagascar	–	C (N)	–	–	–	H (N)	H (S)	Hydro, coal, oil
Southern Madagascar	H (S)	C (N)	–	–	–	H (N)	C (S)	Hydro, coal, oil
Réunion	H (S)	H (N)	–	–	–	H (N)	H (S)	Coal, hydro, oil, biomass
Mauritius	H (S)	H (N)	–	–	–	H (N)	H (S)	Coal, oil, biomass

Northern Mozambique has a high resource-based potential for OTEC. As the national electricity grid is supplied only from geographically distant generation, the predictability and continuity of OTEC may suit the purpose of stabilizing the national grid in the north of the country. However, the region also has unexploited hydropower resources which inevitably will be more cost-efficient to utilize, compared to OTEC. Moreover, the region is known to contain particularly valuable and sensitive marine ecosystems.

In conclusion, the ocean energy resources of the WIO are substantial and may provide propitious future opportunities for the developing power sectors of the region. But the resource availability must be met by the need for energy, to be of any interest. According to the findings of this study, such a match may be found in the small island states of the WIO, and possibly in some remote areas of the African mainland. Ocean energy has already been taken into consideration in the region [12, 13], but if more than a few isolated projects are to be realized, efforts towards successful technology transfer, further deliberated in [105], have to be undertaken.

Acknowledgements

The authors gratefully acknowledge the financial support of Stiftelsen Futura. Further, we are grateful to the UEM-DF Oceanography Team 2005 (Mozambique) for generously providing tidal current data and to Inês Braga Gonçalves and Francisco Francisco for much appreciated support.

References

- [1] Karekezi S, Kimani J. Status of power sector reform in Africa: impact on the poor. *Energy Policy*. 2002;30:923-45.
- [2] Takada M, Rijal K, Morris E. Energizing the Least Developed Countries to Achieve the Millennium Development Goals: The Challenges and Opportunities of Globalization. *Making Globalization Work for the LDCs*. Istanbul: UNDP; 2007. p. 12.
- [3] WB. The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits. Washington DC: World Bank Independent Evaluation Group; 2008.
- [4] Ahlborg H, Hammar L. Drivers and barriers to rural electrification in Tanzania and Mozambique – grid extension, off-grid and renewable energy sources. *World Renewable Energy Congress*. Linköping; 2011. p. 8.
- [5] Weisser D. Power sector reform in small island and developing states: what role for renewable energy technologies? *Renewable and Sustainable Energy Reviews*. 2004;8:101-27.
- [6] Karekezi S, Wangeci J, Manyara E. Sustainable Energy Consumption in Africa. Nairobi: UN-DESA; 2004. p. 63.
- [7] Bugaje IM. Renewable energy for sustainable development in Africa: a review. *Renewable and Sustainable Energy Reviews*. 2006;10:603-12.
- [8] Brew-Hammond A, Kemunoor F. Energy for all in Africa -- to be or not to be? *Current Opinion in Environmental Sustainability*. 2009;1:83-8.
- [9] Dubi AM. Tidal Power Potential in the Submerged Channels of Dar es Salaam Coastal Waters. *Western Indian Ocean J Mar Sci*. 2006;5:95-104.
- [10] EWE. Euro Wave Energy. Available at: <http://www.eurowaveenergy.com2011>. Retrieved June 3, 2011.
- [11] IHTADA. Alternative Energy Tanzania: Wave Power to Replace Gas in Zanzibar? *The Power and Energy Reviews*. Available at: <http://www.ihada.com/2011/05/alternative-energy-tanzania-wave-power-to-replace-gas-in-zanzibar/>. Retrieved July 8, 2011.
- [12] Krock H. Ocean Thermal Energy Conversion. In: Gadonneix P, editor. *2010 Survey of Energy Resources*. London: World Energy Council; 2010. p. 588-602.
- [13] Drouineau M, Maizi N, Assoumou E, Mazauric V. A TIMES model of the Reunion Island for analysing the reliability of electricity supply. *International Energy Workshop*. Stanford; 2011.
- [14] Bhuayan GS. Harnessing the Power of the Oceans. *International Energy Agency OPEN Energy Technology Bulletin*. 2008;1-6.
- [15] Zabihian F, Fung AS. Review of marine renewable energies: Case study of Iran. *Renewable and Sustainable Energy Reviews*. 2011;15:2461-74.
- [16] UNEP. Ocean energy potential of the West African region. UNEP Regional Seas Reports and Studies: United Nations Environment Programme; 1983.
- [17] Khan J, Bhuayan G. *Ocean Energy: Global Technology Development Status*. Surrey: PowerTech Labs; 2009.

- [18] Fröberg E. *Current Power Resource Assessment [Master of Science Thesis]*. Uppsala: Uppsala University; 2006.
- [19] ERRC. *Renewable Energy Scenario to 2040*. Brussels: European Renewable Energy Council; 2004. p. 16.
- [20] Callaghan J. *Future Marine Energy - Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy*. London: The Carbon Trust; 2006. p. 38.
- [21] Esteban M, Leary D. Current developments and future prospects of offshore wind and ocean energy. *Applied Energy*. In Press. Corrected Proof.
- [22] UNFCCC. *United Nations Framework Convention on Climate Change*. Available at: <http://cdm.unfccc.int/Projects/projectsearch.htm2011>. p. 25. Retrieved August 20, 2011.
- [23] Doukas H, Karakosta C, Psarras J. RES technology transfer within the new climate regime: A "helicopter" view under the CDM. *Renewable and Sustainable Energy Reviews*. 2009;13:1138-43.
- [24] Bryden I. *Tidal Energy*. In: Gadonneix P, editor. *2010 Survey of Energy Resources*. London: World Energy Council; 2010. p. 543-61.
- [25] Wang S, Yuan P, Li D, Jiao Y. An overview of ocean renewable energy in China. *Renewable and Sustainable Energy Reviews*. 2011;15:91-111.
- [26] EWURA. Appendix 2A Detailed tariff calculations for year 2011 for the sale of electricity to the main grid in Tanzania. Dar es Salaam: Energy and Water Regulatory Authority; 2011.
- [27] EWURA. Appendix 2B Detailed tariff calculations for year 2011 for the sale of electricity to the mini-grids in Tanzania under standardized small power purchase agreements in Tanzania. Dar es Salaam: Energy and Water Regulatory Authority; 2011.
- [28] Chantier RH, Justus JR. *Ocean Energies - Environmental, Economic and Technological Aspects of Alternative Power Sources*. Elsevier; 1993.
- [29] Thomas G. *The Theory Behind the Conversion of Ocean Wave Energy: a Review*. In: Cruz J, editor. *Ocean Wave Energy - Current Status and Future Perspectives*. Heidelberg: Springer; 2008. p. 41-91.
- [30] Ayub S, Danish SN, Qureshi SR. A novel, cost-effective design to harness ocean energy in the developing countries. *Proceedings of World Academy of Science, Engineering and Technology*. 2011;76:781-6.
- [31] Angelis-Dimakis A, Biberacher M, Dominguez J, Fiorese G, Gadachia S, Gnansounou E, et al. Methods and tools to evaluate the availability of renewable energy sources. *Renewable and Sustainable Energy Reviews*. 2011;15:1182-200.
- [32] Leijon M, Bernhoff H, Berg M, Ågren O. Economical considerations of renewable electric energy production--especially development of wave energy. *Renewable Energy*. 2003;28:1201-9.
- [33] Barstow S, Mark G, Mollison D, Cruz J. *The Wave Energy Resource*. In: Cruz J, editor. *Ocean Wave Energy*. Heidelberg: Springer; 2008. p. 93-132.
- [34] Langhammer O, Haikonen K, Sundberg J. Wave power--Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. *Renewable and Sustainable Energy Reviews*. 2010;14:1329-35.

- [35] Hammar L, Gullström M. Applying Ecological Risk Assessment Methodology for Outlining Ecosystem Effects of Ocean Energy Technologies. 9th European Wave and Tidal Energy Conference. Southampton; 2011.
- [36] Millar DL, Smith HCM, Reeve DE. Modelling analysis of the sensitivity of shoreline change to a wave farm. *Ocean Engineering*. 2007;34:884-901.
- [37] Nihous GC. Mapping available Ocean Thermal Energy Conversion resources around the main Hawaiian Islands with state-of-the-art tools. *Journals of Renewable and Sustainable Energy*. 2010;2.
- [38] Magesh R. OTEC Technology - A World of Clean Energy and Water. Proceedings of the World Congress on Engineering. London 2010.
- [39] Straatman PJT, van Sark WGJHM. A new hybrid ocean thermal energy conversion-Offshore solar pond (OTEC-OSP) design: A cost optimization approach. *Solar Energy*. 2008;82:520-7.
- [40] Yamada N, Hoshi A, Ikegami Y. Performance simulation of solar-boosted ocean thermal energy conversion plant. *Renewable Energy*. 2009;34:1752-8.
- [41] Lennard D. Ocean Thermal Energy Conversion. In: Caillé A, editor. 2007 Survey of Energy Resources. London: World Energy Council; 2007. p. 565-81.
- [42] Mario R. Ocean Thermal Energy Conversion and the Pacific Islands. SOPAC Miscellaneous Report. Suva 2001.
- [43] Griekspoor W. Ocean thermal energy conversion. *Resources and Conservation*. 1981;7:49-60.
- [44] Nihous GC, Syed MA. A financing strategy for small OTEC plants. *Energy Conversion and Management*. 1997;38:201-11.
- [45] Kowalik Z. Tide distribution and tapping into tidal energy. *Oceanologia*. 2004;46:291-331.
- [46] Prandle D. Simple theory for designing tidal power schemes. *Advances in Water Resources*. 1984;7:21-7.
- [47] Ferreira RM, Estefen SF. Alternative concept for tidal power plant with reservoir restrictions. *Renewable Energy*. 2009;34:1151-7.
- [48] Gorlov AM. Tidal Energy. Academic Press; 2001.
- [49] Fay JA, Smachlo MA. Capital cost of small-scale tidal power plants. *Journal of Energy*. 1983;7:536-41.
- [50] Hammons TJ. Energy Potential of the Oceans in Europe and North America: Tidal, Wave, Currents, OTEC and Offshore Wind. *International Journal of Power and Energy Systems*. 2008;28:416-28.
- [51] Charlier RH. Ocean alternative energy - The view from China - 'small is beautiful'. *Renewable & Sustainable Energy Reviews*. 2001;5:403-9.
- [52] Maher P, Smith NPA, Williams AA. Assessment of pico hydro as an option for off-grid electrification in Kenya. *Renewable Energy*. 2003;28:1357-69.
- [53] Hammons TJ. Tidal Power. *Proceedings of the IEEE*. 1993;8:419-33.
- [54] Rourke OF, Boyle F, Reynolds A. Tidal energy update 2009. *Applied Energy*. 2010;87:398-409.
- [55] Gajanayake PA, Furukawa A, Okuma K. Applicability of Darrieus-Type Turbine for Extra-Low Head Tidal Power Generation. *Proceedings of the Eighth International Offshore and Polar Engineering Conference*. Montréal: The International Society of Offshore and Polar Engineers; 1998.
- [56] Khan MJ, Bhuyan G, Iqbal MT, Quaiocoe JE. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Applied Energy*. 2009;86:1823-35.
- [57] Nekrasov AV, Romanenkov DA. Impact of tidal power dams upon tides and environmental conditions in the Sea of Okhotsk. *Continental Shelf Research*. 2010;30:538-52.
- [58] Pethick JS, Morris RKA, Evans DH. Nature conservation implications of a Severn tidal barrage - A preliminary assessment of geomorphological change. *Journal for Nature Conservation*. 2009;17:183-98.
- [59] Frid C, Andonegi E, Depestele J, Judd A, Rihan D, Rogers SI, et al. The environmental interactions of tidal and wave energy generation devices. *Environmental Impact Assessment Review*. In Press, Corrected Proof.
- [60] Fraenkel PL. Power from marine currents. *Proceedings of the Institution of Mechanical Engineers*. 2002;216:1-14.
- [61] Bryden I. Tidal Energy. In: Caillé A, editor. 2007 Survey of Energy Resources. London: World Energy Council; 2007. p. 525-41.
- [62] Grabbe M, Lalander E, Lundin S, Leijon M. A review of the tidal current energy resource in Norway. *Renewable and Sustainable Energy Reviews*. 2009;13:1898-909.
- [63] Inger R, Attrill MJ, Bearhop S, Broderick AC, James Grecian W, Hodgson DJ, et al. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology*. 2009;46:1145-53.
- [64] Minesto. High Efficiency - Low Impact. Available at: <http://www.minesto.com/2011>. Retrieved July 20, 2011.
- [65] Finkl CW, Charlier R. Electrical power generation from ocean currents in the Straits of Florida: Some environmental considerations. *Renewable and Sustainable Energy Reviews*. 2009;13:2597-604.
- [66] Hammar L, Ehnberg J. Ocean Energy Resources in the Western Indian Ocean. Gothenburg: Energy and Environment; 2011.
- [67] Spalding-Fecher R. Health benefits of electrification in developing countries: a quantitative assessment in South Africa. *Energy for Sustainable Development*. 2005;9:53-62.
- [68] Ngusuru A. Geological History Climate and Oceanography. In: Richmond MD, editor. *A Field Guide to the Seashores of Eastern Africa and the Western Indian Ocean Islands*. Milano: Sida/SAREC; 2002. p. 12-6.
- [69] Mavume A, Brundrit G. Sea level rise and cyclone analysis. In: van Logchem B, Brito R, editors. *INGC Climate Change Report: Study on the impact of climate change on disaster risk in Mozambique*. Maputo: Instituto Nacional de Gestão de Calamidades; 2009. p. 33-66.
- [70] Salman G, Abdul I. Development of the Mozambique and Rovuma Basins, offshore Mozambique. *Sedimentary Geology*. 1995;96:7-41.

- [71] Quayle RG, Changery MJ. Estimates of Coastal Deepwater Wave Energy Potential for the World. *Oceans 81*. Boston 1981. p. 903-7.
- [72] Krogsstad HE, F. Barstow S. Satellite wave measurements for coastal engineering applications. *Coastal Engineering*. 1999;37:283-307.
- [73] Cornett AM. A Global Wave Energy Resource Assessment. Ottawa: Canadian Hydraulic Centre; 2008.
- [74] Folley M, Whitaker T, Henry A. The performance of a wave energy converter in shallow water. 6th European Wave and Tidal Energy Conference. Glasgow 2005. p. 133-9.
- [75] Masalu DCP, Ababio SD, Beebejann M, Diallo A, Dovie EK, Maueua C, et al. African Marine Atlas. Intergovernmental Oceanographic Commission; 2006.
- [76] Wessel P, Smith WHF. A Global Self-consistent, Hierarchical, High-resolution Shoreline Database. *J Geophys Res*. 1996;101:8741-3.
- [77] BODC. Centenary Edition of the GEBCO Digital Atlas. Liverpool: British Oceanographic Data Centre; 2003. Available at: <http://iodeweb2.vliz.be/omap/OMAP/index.htm>. Retrieved March 10, 2011.
- [78] Conkright ME, Locantini RA, Garcia HE, O'Brien TD, Boyer TP, Stephens C, et al. World Ocean Atlas: Objective Analyses, Data Statistics, and Figures. Silver Spring: National Oceanographic Data Center; 2002.
- [79] Vega LA. Hawaii National Marine Renewable Energy Center. 2011. Available at: <http://hinnmrec.hawaii.edu/ongoing-projects/otec-thermal-resource/>. Retrieved May 10, 2011.
- [80] Cooke A. Marine and coastal ecosystems of Madagascar. ReefDoctor 2002. Available at: http://www.reefdoctor.org/downloads/science/background_papers/andrewcooke2002.pdf. Retrieved June 4, 2011.
- [81] Ninyete IK, Mahongo SB. National report of the United Republic of Tanzania on sea level measurements. Dar es Salaam: Tanzania Ports Authority; 2007.
- [82] Magori C. Tidal analysis and predictions in the Western Indian Ocean. Mombasa: Kenya Marine and Fisheries Research Institute; 2008.
- [83] INAHINA. Tabela de marés 2010 Moçambique. Maputo: Instituto Nacional de Hidrografia e Navegação (INAHINA); 2009.
- [84] INAHINA. Tabela de marés 2011 Moçambique. Maputo: Instituto Nacional de Hidrografia e Navegação (INAHINA); 2010.
- [85] Lwiza KMM. Beach erosion north of Dar es Salaam IOC-UNEP-WNO-SAREC Planning Workshop on An Integrated Approach to Coastal Erosion, Sea Level Changes and Their Impacts. Zanzibar: UNESCO; 1996. p. 108-12.
- [86] Mavume AF. Throughflow in Ponta Torres strait - Inhaca, Mozambique - in relation to sea level differences, tides, winds and wave set-up [Licentiate Thesis]. Gothenburg: Gothenburg University; 2000.
- [87] Kitheka JU. Groundwater Outflow and its Linkage to Coastal Circulation in a Mangrove-fringed Creek in Kenya. *Estuarine, Coastal and Shelf Science*. 1998;47:63-75.
- [88] Barnes DKA, Whittington M. Biomechanics and mass mortality of erect bryozoans on a coral reef. *J Mar Biol Ass UK*. 1999;79:745-9.

- [89] Mavume A, Maluane B, Silva A, Mulchande E, Pereira O, Guissamulo A. Dugongo Ecology and Bazaruto Habitat Mapping Project 2004-2005. Maputo: UEM-DF Oceanography Team 2005 Unpublished results.
- [90] Hagerman G, Polagye B, Bedard R, Previste M. Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TTSEC) Devices. Electric Power Research Institute; 2006.
- [91] DiMarco SF, Chapman P, Nowlin WDJ, Hacker P, Donohue K, Luther M, et al. Volume transport and property distributions of the Mozambique Channel. *Deep-Sea Research II*. 2002;49:1481-11.
- [92] Lumpkin R, Pazos M. Measuring surface currents with Surface Velocity Program drifters: the instrument, its data, and some recent results. Miami: Atlantic Oceanographic and Meteorological Laboratory; 2005.
- [93] Cutler AN, Swallow JC. Surface currents of the Indian Ocean (to 25°S, 100°E): compiled from historical data archived by the Meteorological Office. Bracknell: Institute of Oceanographic Sciences; 1984.
- [94] Richardson PL. Drifting in the wind: leeway error in shipdrift data. *Deep Sea Research Part I: Oceanographic Research Papers*. 1997;44:1877-903.
- [95] Seychelles. Country Brief New York: eStandardsForum; 2010.
- [96] Comoros. Country Brief New York: eStandardsForum; 2010.
- [97] Madagascar. Country Brief New York: eStandardsForum; 2009.
- [98] Mozambique. Country Brief New York: eStandardsForum; 2009.
- [99] Mauritius. Country Brief New York: eStandardsForum; 2010.
- [100] Stackhouse JPW. Surface meteorology and Solar Energy. Atmospheric Science Data Center; 2011. Available at: <http://eosweb.larc.nasa.gov/>. Retrieved June 5, 2011.
- [101] Chapman P, Marco SFD, Davis RE, Coward AC. Flow at intermediate depths around Madagascar based on ALACE float trajectories. *Deep Sea Research Part II: Topical Studies in Oceanography*. 2003;50:1957-86.
- [102] Pelc R, Fujita RM. Renewable energy from the ocean. *Marine Policy*. 2002;26:471-9.
- [103] Carbone F, Accordi G. The Indian Ocean Coast of Somalia. *Marine Pollution Bulletin*. 2000;41:141-59.
- [104] Agion T. Environment and Social Impact Assessment Study: Submarine cable Project. La Ciotat; 2010.
- [105] Karakosta C, Doukas H, Psarras J. Technology transfer through climate change: Setting a sustainable energy pattern. *Renewable and Sustainable Energy Reviews*. 2010;14:1546-57.

PAPER II

Site-Screening Method for Micro Tidal Current Turbines and a Case Study in Mozambique

Linus Hammar¹, Jimmy Ehnberg², Alberto Mavume³, Francisco³
Sverker Molander¹

¹ Energy and Environment, Chalmers University of Technology, Rännvägen 6, 412 96 Gothenburg, Sweden.
² Swedenpower, 401 75 Gothenburg, Sweden.
³ Climate & Disaster Research Group - SECCHD, Department of Physics, Faculty of Sciences, Eduardo Mondlane
University, PO Box 257, Maputo, Mozambique.

Abstract

A broad spectrum of tidal current turbines (TCT) is emerging, the majority focusing on large-scale extraction of renewable energy at global tidal hot-spots. Concurrently, some developing prototypes are small and may be suitable also for micro-scale applications (micro-TCT) in remote areas, such as decentralized electrification in developing countries where fuel-independent energy systems with high power predictability are particularly important. In shallow waters the force of tidal currents varies considerably over short distances and very site-specific measurements are important for assessment of localization, but are also expensive. For micro-TCT to be pertinent site-screening and evaluation has to be inexpensive and low-cost methods must be developed. This study proposes a simplified tidal model that is calibrated to site-specific conditions by short-term observations. By measurements comprising down to 8% of the monthly tidal period the potential power output can be estimated, with uncertainty intervals up to $\pm 20\%$, for currents favourable to micro-TCT. This site-screening method was tested at five sites in Mozambique where near-shore tidal currents were measured with lightweight current meters. At three of the sites currents were estimated to exceed 1 m s^{-1} and power output was calculated based on technical assumptions for a micro-TCT device. Results are discussed from the perspective of decentralized grid remote area electrification.

1. Introduction

Tidal current turbines (TCT) convert kinetic energy from fast-flowing tidal currents into electricity. The TCT technologies are still at a formative stage and comprise a wide diversity of different designs [1-5]. The predictability of tides provides a great advantage and is one major reason for the substantial interest that lately has been given to tidal power [3, 5-8]. Despite limited knowledge of the occurrence of strong tidal currents in most parts of the world the global extractable resource is presumed to be substantial [5, 9] and projections for TCT technology show an extensive growth from 2020 [10, 11]. Being both a renewable and predictable energy source tidal power may become one of many important pieces in the jigsaw of cleaner global energy supply. More modestly, it has been suggested that immediate opportunities for TCTs reside in providing power to rural and island communities [2].

Most of the different TCT technologies rely on submerged or floating generators driven by horizontal or vertical turbines, with rotors forced by the currents. The rotor dimensions are heavily influential on energy capture, but large rotors attain massive loads from currents resulting in stress on material and large foundations. Within TCT development the main focus has been on relatively large solutions with tidal farms of tens to hundreds of units, each with a capacity of 300 kW to 2 MW, operating in fast flowing currents above 2 m s^{-1} [12]. Devices set for these conditions require weight dimensions of up to hundreds of tons per unit [13] which imply high costs of manufacturing and installation.

Distinguishable from the large-scale approach are small units rated at about 5-25 kW, here referred to as micro-TCT. Of the 39 TCT devices reviewed by the International Energy Agency [12], about five can be classified as micro-TCT. Micro-TCTs are lightweight, can be deployed in shallow waters, and may be adapted to the conditions of less harsh sites and slower current velocities. One example is the vertical axis turbine presented by Grabbe [14], where low cut-in speed and high generator efficiency at low speed increase the period of power generation as it operates over a larger part of the tidal cycle.

If smaller and less harsh sites can be utilized the number of potential sites increases, although the extractable power at such sites may be relatively small. In a review of the Norwegian tidal current resource 13% of the theoretical resource was estimated to reside in sites shallower than 20 m, and 6% at sites with currents below 2 m s^{-1} mean maximum spring speed [8]. Micro-scale extraction may typically be of interest where access to predictable renewable energy is of certain value, such as remote and less developed locations. As noted

by [15] on small-scale wave power, electricity *access* and fuel independence, may be regarded as surplus values in developing countries.

Noteworthy, the micro-scale perspective is not new; already fifty years ago about 40 tidal power barrages, with a total capacity of 583 kW, supplied electricity to Chinese agriculture [16]. A similar approach, electrification of remote communities by use of small tidal barrages, was suggested by Anderson et al. [17] in 1993, who argued that conversion of old mechanical tidal mills in rural villages into micro power plants would provide enough electricity to meet the needs of rural communities in Brazil. Decentralized electrification is an issue of great importance both for remote island communities and countries where the costly extension of national transmission grids is still in development [18, 19]. For example, low rural electrification levels and expensive diesel generators in Tanzania have raised the standardized purchase tariff for electricity sold by small producers to decentralized grids to 25¢ per kWh, which is >300% of the purchase tariff for electricity sold to the main grid [20, 21].

With local use of renewable energy the running costs are basically limited to maintenance. Micro solar PV systems have frequently been used for these purposes but more power-intense sources are needed if electricity is to be used for economically productive purposes [22, 23]. One suggestion has been micro-scale river current energy conversion [24]; similarly micro tidal power could contribute where available. Again, China is a good example on taking early action. There has been substantial research and development in tidal power, including micro-TCT in decentralized grids, and the source is expected to take an important role in the future energy structure [25].

As tidal currents are very confined and directly dependent on local bathymetry it is not straightforward to locate appropriate sites. At a strategic level tidal current resources can be estimated either by modelling water movement based on tidal range (water level) data and coastal morphology [26-28], or by using existing information of the peak current velocities at specific sites [8, 13]. Assumptions are necessary in all modelling and uncertainties increase when large-scale assessments are transferred to site-specific evaluations. For adequate calculation of potential power output at a specific site a detailed characterization of the local currents is required [29-31], with suggested lowest sample series of one synodic period (29 days) [7]. In near-shore shallow water, where the spatial variation of currents is particularly high, several nearby sites may have to be investigated to identify the most promising.

In remote areas, however, long-term field measurements with expensive equipment are logistically complicated and costly, even more so if the project takes place in a developing country with little infrastructure. One month of measurements with Acoustic Doppler Current

Profiler (ADCP) equipment at a remote location, including safeguarding of equipment and a vessel for deployment and recovery, would likely imply huge costs in relation to the output and economical return of any micro-TCT. Here, initial data sampling will inevitably consume a disproportionately large share of the project and for this reason adapted low-cost methods for site-screening and preliminary evaluation will likely be necessary if micro-TCT technology is to be of interest for the niche market of remote area electrification.

In this paper we have developed and tested a simple low-cost method for site-specific evaluations of the potential for micro-TCT. Short-term observations were collected by lightweight current meters in shallow straits of Mozambique; the most influential site-specific tidal characteristics were then extracted and used to calibrate a basic tidal model, in turn producing site-specific and time resolved estimations of electric power output. The resulting power output and availability over time were examined in terms of usefulness for remote rural villages. The study aims to exemplify how site evaluations for micro-TCTs can be conducted with a fraction of the efforts required for fulltime measurements.

2. Methods

2.1. Main characteristics of tides

Tidal currents are induced by water level fluctuations originating from the Earth rotation in combination with the gravitational forces between the Earth, the moon, and the sun. The magnitude of tides at a specific location is further determined by coastal geometry, i.e. shoreline and bathymetry [32, 33]. Although weather conditions have some influence, tidal elevations and their induced currents are essentially predictable. The dominant astronomical force, the moon, creates a tidal lunar day cycle of 24 h 50 min. Each lunar day comprise one or two tidal periods for diurnal and semidiurnal tides respectively. The moon position in relation to Earth and sun adds a monthly cycle (29.5 days). The tides are magnified when the three astronomic bodies are positioned in line (spring tides) and are weakened when they form an angle close or equal to 90° (neap tides); a monthly cycle covers two periods of spring and neap tides. Typically, spring tides create a tidal range twice the size of the neap tidal range [7]. Altogether, these major constituents produce a double sinusoid tidal pattern. In addition, the first and the second tide each lunar day differ in consequence of the Earth rotation, and the moon's altitude over Earth affects the magnitude of spring and neaps tides.

2.2. Technical assumptions for micro-TCT energy conversion

TCT prototypes encompass a variety of technical concepts including horizontal and vertical turbines, some of which are ducted while others are open [12, 34]. Apart from size, several factors influence how well a certain device suits the particular conditions of micro-scale implementation; turbine cut-in speed, generator efficiency at lower speeds, and insensitivity to water flow direction all influence the power generation pattern over the tidal cycle. Moreover, flexibility and costs of installation are affected by mooring technique; floating devices are likely preferable for micro-scale applications. Most importantly, high robustness and facilitated maintenance are of critical importance at remote locations.

In this study we have based the technical assumptions on currently available information on micro-TCT, mainly from [13] and [29]. The assumptions correspond to a hypothetical lightweight 15 kW micro-TCT consisting of three vertical-axis turbines mounted on a ducted floating structure: cut-in speed $v_{cut-in}=0.5$, rotor area $A_r=15 \text{ m}^2$, water density $\rho=1.025 \text{ kg m}^{-3}$ (Fig. 1). Based on [29], the total weight of the turbines would be about 550 kg. The device-specific power coefficient, C_p , varies throughout the tidal cycle [31] as it consists of turbine efficiency (C_t), drive train efficiency (C_d), generator efficiency (C_g), and power conditioning (C_c). A typical value of C_p for a TCT is about 0.40 at rated speed [7]. Micro-TCTs are likely to be less efficient, but C_p can be strongly improved by mounting a duct over the turbine [30, 35]. For the ducted micro-TCT in this study we assumed a

$$P_e = A_r \cdot \rho \cdot C_p(v) \cdot v^3$$

$$A \quad v \geq v_{cut-in}$$

(1)

power (P_e) can be calculated by Equation 1:

The tidal fluctuations induce flood currents towards the coast and receding ebb currents in opposite direction. Flood and ebb currents are thus variable but predictable over time. Exaggerated currents are typically found in association with straits and peninsulas [29]. The kinetic energy in flowing water is cubed to the velocity, and the conversion into electric

conservative turbine efficiency of $C_t=0.45$ and the water-to-wire efficiency was calculated by assuming $C_d=0.96$, $C_e=0.98$ and the generator efficiency function demonstrated by Grabbe [14].

It has been estimated that extraction of more than 10% of the energy from a natural flow may impact the current regime, bringing about both technical and environmental implications [2, 6]. However, in this micro-scale approach the extraction is assumed to be lower.

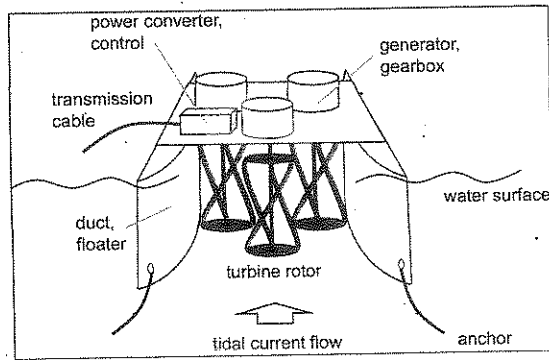


Figure 1. Sketch of the hypothetical 15 kW micro-TCT used for power calculations in this study. Illustration developed with inspiration from [24].

2.3. Field sampling

Short-term observations of tidal current velocities, v , were sampled at remote locations in Mozambique, a country with 2 470 km of coastline, mean tidal ranges of 1.9 to 3.5 m, and largely unknown tidal currents (Fig 2). We used published observations [36, 37] of strong tidal currents to identify areas of interest for sampling; these were Inhaca Island, the Quirimbas Archipelago, and Bazaruto Island. For Bazaruto, we attained previously collected unpublished short-term observations from [38]. At Inhaca and Quirimbas, sampling sites were selected on the basis of requested local knowledge from fishermen and vessel staffs about sites of particularly strong tidal currents in the proximity of settlements.

Inhaca Island constitutes an elevated sand bank between the Indian Ocean and Maputo Bay, only separated from mainland by a shallow strait in which currents are generated mainly by

tides [37]. Observations were collected in one of many narrow tidal channels (site 1-Inhaca) and in the actual strait (site 2-Inhaca). The Quirimbas Archipelago consists of several scattered coral islands, creating inlets and channels with reported strong tidal currents [36]. In this area sampling was carried out at two sites; a bay inlet (site 3-Quirimbas) and a coral-based channel (site 4-Quirimbas). The sampling was carried out in June-August 2010 by use of a lightweight Doppler current meter (ALEC Infinity-EM, 10 samples per minute) mounted at a depth of 2-3 meters from the surface. As the measurements were taken at the same depth as the rotor of the suggested micro-TCT no depth adjustments of current velocity were undertaken. At each site, two time-separated sets of short-term observations were collected, each set covering 1 to 5 flow peaks (one flow peak represents the water velocity during ebb or flood current).

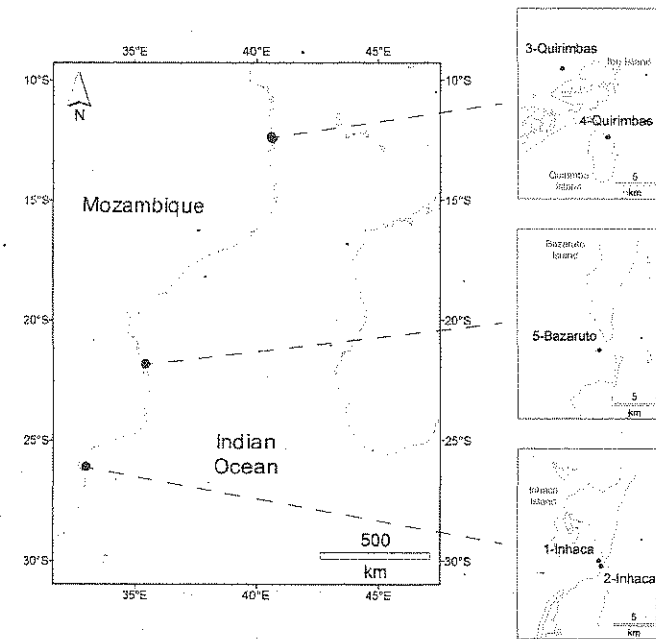


Figure 2. Location of case-study sites in Mozambique; 1-Inhaca, 2-Inhaca, 3-Quirimbas, 4-Quirimbas, and 5-Bazaruto.

Similarly to Inhaca, Bazarruto Island constitutes an elongated sandbank facing the Indian Ocean. Strong tidal currents are generated in the strait to mainland (site 5-Bazarruto). Three time-separated arbitrarily selected sets of observations, each comprising 4 flow peaks, were extracted from full 10-days series collected in 2004-2005 by a Doppler current meter (Aanderaa RCM9, 6 samples per hour) mounted at 1 m from the bottom in 23 m depth [38]. The 10^{th} power law [7] was used to calculate the speed at turbine depth, 3 m from surface. The short-term observations from the five sites (Table 1) were used to generate site-specific estimations of the monthly variation of v by calibrating the tidal model given by Equation 2. Potential power output was estimated on the basis of Equation 1 and the technical assumptions (2.2.).

Table 1. Location, site depth at mean sea level, environment, and sampling effort for the five investigated sites in Mozambique. Sampling effort is given as number of days allocated for sampling and as measurement time in proportion to the full tidal period (14.5 days).

Sample site	Lat.	Lon.	Site depth (m)	Environment	Sampling effort (days)
1-Inhaca	S 26.0748°	S 32.9520°	17	Tidal channel	2 14%
2-Inhaca	S 26.0810°	S 32.9548°	10	Strait	1.5 8%
3-Quirimbas	S 12.3337°	S 40.5693°	7	Bay entrance	2 14%
4-Quirimbas	S 12.4124°	S 40.6215°	7	Reef channel	2 14%
5-Bazarruto	S 21.8049°	S 35.4449°	23	Strait	3 21%

In order to reproduce v over the monthly tidal period a simplified tidal model was developed from [39]. The model includes three site-specific coefficients: (i) the maximum spring speed (MSS), (ii) the maximum neap speed (MNS), and (iii) the ratio between flood and ebb currents (d_e) (Fig 3). The MSS and MNS determine the dimensions of the sinusoidal curve, including the daily period (12 h 25 min from one low tide to the next low tide) and the monthly period (14.5 days from neap to next neap). As most energy resides in the highest flows, adequate estimations of MSS are crucial for power calculations. Moreover, knowledge of MNS is

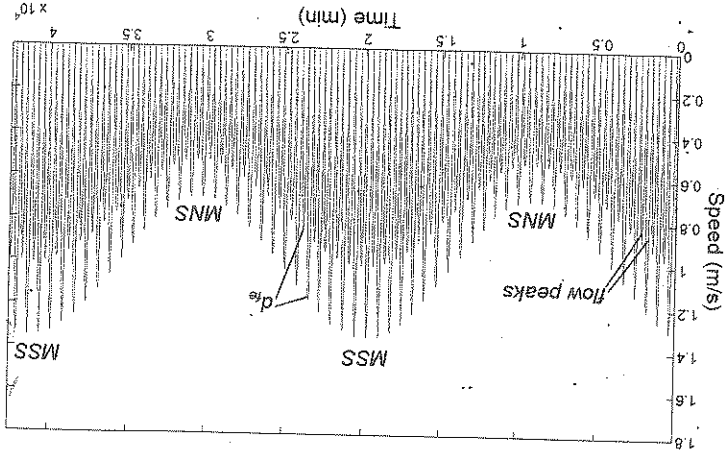


Figure 3. Schematic illustration of the three coefficients used to calibrate the tidal model: maximum spring speed (MSS), maximum neap speed (MNS), and the flood/ebb ratio (d_e).

particularly, important for decentralized electricity grids since it determines the power availability during the two weeks per month of lower energy intensity. The difference between flood and ebb currents, d_e , describes the magnitude of every second flow and consequently has a large impact on the total generation and the temporal variations of power [13] (of particular importance for decentralized systems). The applied semidiurnal tidal current model is expressed as (Eq. 2):

$$v = \begin{cases} \left[MSS + MNS \cos\left(\frac{2\pi}{T_2} t\right) \right] \cos\left(\frac{2\pi}{T_1} t\right) & nT_2 \leq t \leq (2n+1)T_2 \\ -d_e \left[MSS + MNS \cos\left(\frac{2\pi}{T_2} t\right) \right] \cos\left(\frac{2\pi}{T_1} t\right) & (2n+1)T_2 < t < (n+1)T_2 \end{cases} \quad n = 1, 2, 3, \dots \quad (2)$$

where t is time in reference to the tidal cycle, T_1 is the diurnal tidal period (745 min), and T_2 is the monthly tidal period (21262 min). The sampled short-term observations were used to calibrate the tidal model and compute the site-specific temporal distribution of current velocity. First, the d_e coefficient was estimated

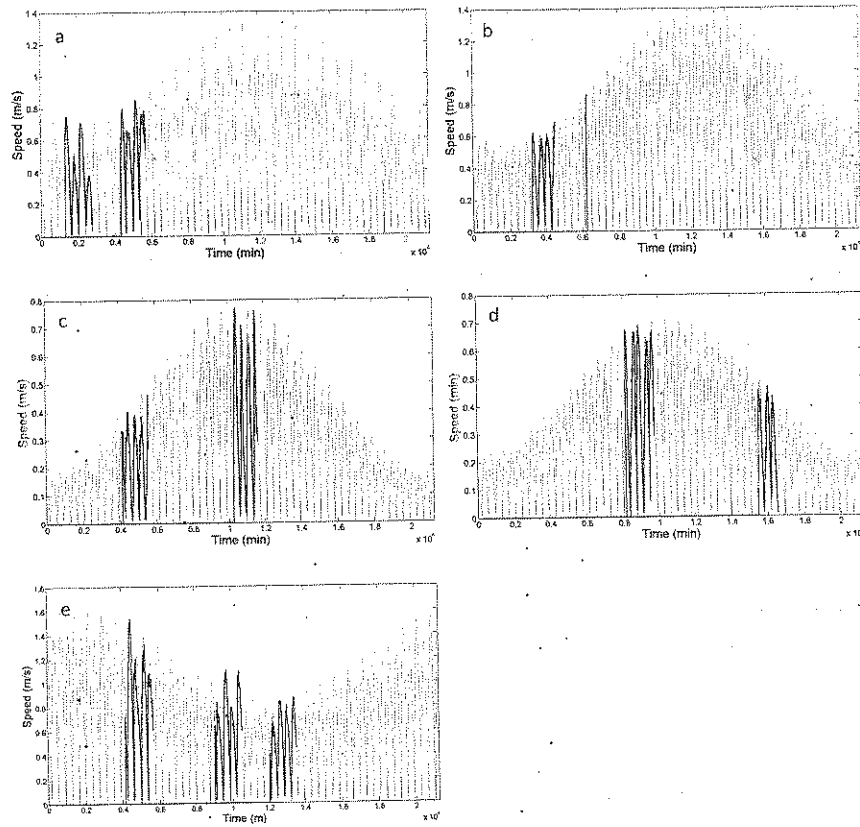


Figure 4a-e. The sampled short-term observations were superimposed to the generic tidal model (14.5 days) and used for estimating the tidal coefficients by adjusting until best-fit between observations and model. Figures show sites (a) 1-Inhaca, (b) 2-Inhaca, (c) 3-Quirimbas, (d) 4-Quirimbas, and (e) 5-Bazaruto. Note: y axis max speed values (m/s) a-b = 1.4; c-d = 0.8; e = 1.8; x axis time 0–14.5 days.

from sample data by calculating the average ratio between maximum speed of subsequent peaks (flood and ebb currents). Secondly, the sample data was superimposed onto the tidal current model (Eq. 2), synchronized in time with reference to spring/neap, and values of MSS and MNS were adjusted until best fit between flow peaks in sample data and model (Fig 4a-e). Hereby, the true values of MSS , MNS , and d_{fe} were estimated from low amounts of data under

the assumption of a double sinusoid tidal cycle given by Equation 2. The potential TCT power output was further calculated by inserting the modelled v into Equation 1.

2.5. Method validation

A previously published data set [40] of tidal currents from southern Mozambique (Portuguese Island) was used for method validation. The used data comprises flow peaks over two monthly tidal periods (29 days). The model accuracy and precision were calculated as the bias and standard error from sample estimates of the coefficients MSS , MNS , and d_{fe} in relation to their true values. Three levels of data input were tested: combinations of '4+4+4', '4+4', and '4+1' flow peaks, with the criteria of at least a 4 flow peaks separation between sets. The three tested combinations correspond to measurements during 'three separate days', 'two separate days', and 'one day plus one ebb/flood', respectively.

Table 2. Results from the validation process where tidal coefficients were estimated in accordance with the proposed method and compared with the true values from the same data set. Twenty trials with randomly selected data were run for each level of data (number of flow peaks); $n=20$. Accuracy was measured as the bias, which is the average divergence between estimates and true values. Precision was measured as the standard error (S.E.) between estimates (samples) and true values. The corresponding uncertainty in terms of power output was calculated for a micro-TCT at two typical tidal current settings: (A) MSS 2.00, MNS 1.59, d_{fe} 0.85, and (B) MSS 1.5, MNS 1.19, d_{fe} 0.85.

Number of flow peaks	Coefficient	Bias	±S.E.	Corresponding uncertainty (power)
4+4+4	MSS	0.007	0.025	A: -10 – 12 %
	MNS	0.003	0.046	B: -12 – 15 %
	d_{fe}	-0.001	0.041	
4+4	MSS	0.020	0.042	A: -11 – 16 %
	MNS	-0.002	0.046	B: -12 – 20 %
	d_{fe}	0.001	0.044	
4+1	MSS	-0.005	0.058	A: -15 – 16 %
	MNS	0.013	0.058	B: -19 – 19 %
	d_{fe}	0.004	0.045	

3. Results

3.1. Method validity

The validation indicated a high accuracy and a precision that may be acceptable for screening and first site evaluation purposes, even for very short sample series of tidal current speed (Table 2). The corresponding uncertainty in terms of power output differs largely between sites as the inherent energy is cubed to water velocity. For sites with peak currents around $1.5\text{--}2\text{ m s}^{-1}$ the uncertainty range was estimated to be in the order of $\pm 20\%$ for the lowest amounts of data that were tested; with the use of more data the uncertainty decreased. It should be noted that the validation was based on data from a single location with semidiurnal tides.

3.2. Micro-TCT power output at investigated sites

The estimated tidal coefficients and power output from one micro-TCT unit operating at investigated sites are given in Table 3. In Quirimbas Archipelago the maximum current speed was below 1 m s^{-1} for both investigated sites and the power potential was considered negligible. Fig. 5 a-c demonstrates the power output for the three remaining sites.

Table 3. Estimated site-specific coefficients, power output per tidal period (14.5 days), and power availability (generation) over time as percentage of the tidal period.

Site	Input-data	Coefficients	Power	Power availability (%)
	(flow peaks)	MSS	MNS	d_p
			(kWh)	
			> 0 W	$\geq 1\text{ kW}$
				$\geq 5\text{ kW}$
1-Inhaca	'4+4'	1.35	0.70	0.75
2-Inhaca	'3+1'	1.40	0.55	0.93
3-Quirimbas	'4+4'	0.77	0.15	0.90
4-Quirimbas	'5+3'	0.71	0.23	0.94
5-Bazaruto	'4+4+4'	1.61	0.85	0.87
			1400	69
			42	11
			79	18
			874	58
			47	47
			58	47
			63	9
			69	0
			30	0

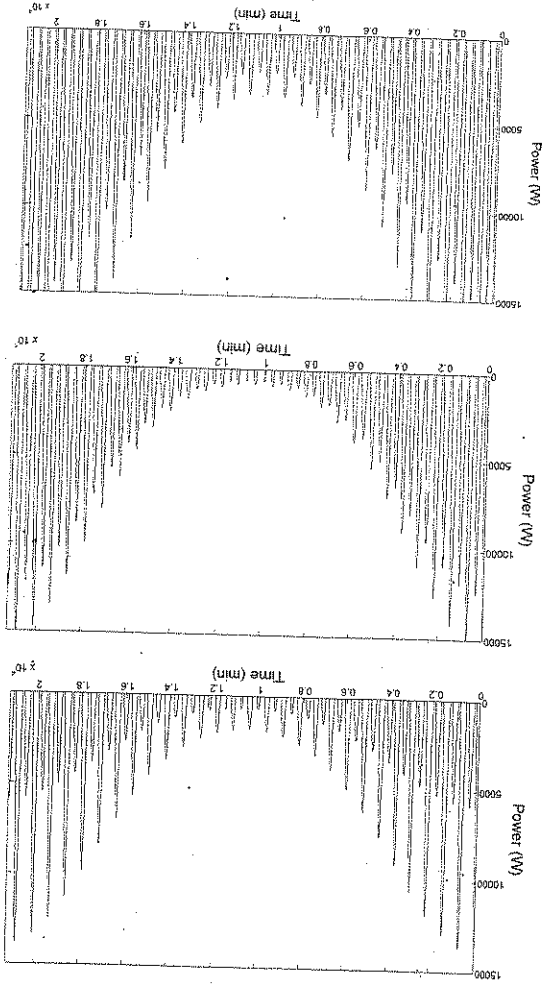


Figure 5a-c. Temporal distribution of power from one micro-TCT unit after calibrating the model to short-term observations from the Mozambican case-study sites: (a) 1-Inhaca, (b) 2-Inhaca, (c) 5-Bazaruto. Diagrams comprise a 14.5 days tidal cycle and the calculations are based on the technical assumptions presented in 2.2. Note: y axis power 0–15 kW; x axis time 0–14.5 days.

The highest power potential, and an estimated current peak of 1.61 m s^{-1} , was found at site 5-Bazaruto while current peaks up to 1.40 m s^{-1} were estimated at site 2-Inhaca. The observations from site 2-Inhaca covered only 8% of the tidal period. However, the result is supported by previously published measurements from the same area ($MSS 1.45 \text{ m s}^{-1}$) [37]. The potential power pattern differs substantially between the two Inhaca sites even though the total power output is comparable and average power availability is similar. At site 2-Inhaca power is more evenly distributed within days (ebb and flood) as a result of a higher d_{f0} (Fig. 5 b), while site 1-Inhaca provides somewhat more power during neap as a consequence of a higher MNS . The temporal availability of electricity is similar for both sites, 58%, but differs regarding the availability of power exceeding 5 kW (19 and 13% respectively). At Bazaruto, however, the temporal power availability is 69% and 5 kW is available during 30% of time. Here, the power output is limited by the technical assumptions of the study, the rated power of the device.

While the investigated sites in the Quirimbas Archipelago did not reveal any currents of interest, this example rather demonstrates the difficulties of site-screening on the basis of vague local information on current velocities.

4. Discussion

4.1. Usefulness of micro-TCT electricity

Mozambique has a rural electrification level below 3% and, similarly to other countries in East Africa, there are vast areas which will not be reached by the national electricity grid within the foreseeable future [19]. Until then, decentralized micro-grids or autonomous systems are the only options if electricity is to be supplied. The demand for electric power is generally limited under such rural conditions, with first loads being lighting and small appliances and generic household consumptions being about 150-300W [41, 42]. A common experience regarding rural electrification is that productive use of electricity, that is uses which increase income by production, refining, manufacturing or commerce, is necessary for actual effects on economic development [22, 43-46]. Small-scale productive uses may be freezers for fish, grinding mills and irrigation used in agriculture, or saw mills, carpentries and manufacturing workshops for refinery of products. The electricity consumption from such loads typically ranges from 1 to 20 kW [41, 43].

Productive use loads are generally stochastic, as they are known to magnitude but not fully known in relation to time. In a small decentralized grid, or autonomous system, most productive usages would turn out as critic-stochastic loads risking damaging the electrical system. Hence, in order to use tidal power in decentralized grids these loads must be made deterministic. Water pumping, freezing and grinding mills are examples of productive electricity loads easily made deterministic, as they can be tuned to available power (here: tidal predictions). Further, with heavy batteries or other energy storage micro-TCT can provide invariable power output from sites where the available tidal energy is sufficient on a monthly basis – such battery-based solutions are expensive though.

Under remote village conditions one or a few micro-TCT at site 5-Bazaruto could generate a good supplement of power. The power output per unit exceeds 5 kW over 30% of the time and reaches 15 kW during spring tide. With deterministic loads and batteries both village-level production and households could be supplied. At site 2-Inhaca the monthly availability of power above 5 kW was estimated to 19%. However, throughout the 7 days neap period power never reaches this level. With one or few units in operation the produced electricity would only be able to serve household-level loads most of the time.

At Inhaca it was further illustrated how nearby sites can differ strongly in MNS (Fig. 5), of importance for the power availability during neap, despite having quite similar MSS and being part of the same tidal channel.

4.2. Realization of micro-TCT

For micro-TCTs to become an option for decentralized electrification of remote areas large volumes and package solutions of operational units would be necessary to keep down unit costs and ensure maintenance capacity. Low-cost site-screening and evaluation methods, as the one presented in this paper, will be necessary. Our example showed how short-term observations down to 8% of the monthly tidal period can be used for comparing and briefly evaluating sites. Thus, preliminary field sampling efforts can be reduced by a factor of 5-10 (depending on the accepted level of uncertainty). While the case-study in this paper is carried out in Mozambique, there are many developing countries with the combination of strong tides and dispersed populations living in remote areas without access to grid-connected electricity; some examples are Brazil, India, Indonesia, and the Philippines.

In addition to the technical considerations reflected in this study, there are substantial challenges associated with management and local absorption of technology [47]; moreover, the environmental implications of TCT in shallow waters are yet to be determined [48].

4.3. Limitations

The applied method does not separate between tidal constituents and non-tidal constituents such as weather related variations, nor does it account for monthly variations due to the distance between moon and Earth. However, because current velocity is correlated to evaluation, with knowledge of the currents at a particular month ordinary tidal models can be used to extrapolate over years [7]. The limitations of the method imply that estimated tidal currents would inevitably be somewhat inaccurate; this must be acknowledged when using the method for evaluating sites. For observations shorter than four flow peaks (24 h) the repeated difference in magnitude between two subsequent tides during a tidal day may induce significant errors in model calibration. In addition, time-separation of observations becomes increasingly important for model calibration when observations are few.

5. Conclusion

The applied method offers a low-cost option for micro-TCT site-screening in remote areas, facilitating comparisons and evaluations of the usefulness of power output between potential sites. At the cost of reduced accuracy compared to long-term measurements, the logistic and technical requirements of the method are low. It is argued that simplified screening methods of this kind are necessary for micro-TCT to become a realistic option at the niche market of decentralized electrification in remote developing areas. Among the investigated sites in Mozambique, Bazantu Island has tidal currents in which even a small number of micro-TCT would provide useful amounts of electricity. The currents at Inhaca were moderate and of doubtful use for other than household-level loads. The disproportional variation between MSS , MNS and d_p between nearby sites stresses the importance of several site-specific observations at an early stage of screening for micro-TCT potential in shallow water with moderate tides.

Acknowledgements

The authors wish to express their gratitude to B. Malaquene, A. Silva, E. Mulchande, O. Pereira, and A. Guissamulo for generously providing tidal current data from Bazantu. Further, valuable contributions have been given by Mr. Pedro Calixto at the Mozambican Ministry of Energy, and Inês Gonçalves at Gothenburg University. The study was conducted with financial support from Stiftelsen Futura and the AForsk Foundation.

References

- [1] J.A. Clarke, G. Connor, A.D. Grant, C.M. Johnstone, Regulating the output characteristics of tidal current power stations to facilitate better base load matching over the lunar cycle, *Renewable Energy*, 31 (2006) 173-180.
- [2] I. Bryden, *Tidal Energy*, in: N. Zupanc, A.W. Clarke, J.A. Trimmaman, J.K. Mehta (Eds.), *Survey of Energy Resources*, World Energy Council, London, 2007, pp. 525-535.
- [3] E. Block, *Tidal power: an update*, *Renewable Energy Focus*, 9 (2007) 58-61.
- [4] H.C. Soerensen, S. Naef, Report on technical specification of reference technologies (wave and tidal power plant), European Commission Sixth Framework Programme. Available online: <http://www.needs-project.org/>, 2008.
- [5] O.F. Rourke, F. Boyle, A. Reynolds, *Tidal energy update 2009*, *Applied Energy*, 87 (2010) 398-409.
- [6] I.G. Bryden, T. Grimsied, G.T. Melville, Assessing the potential of a simple tidal channel to deliver useful energy, *Applied Ocean Research*, 26 (2004) 198-204.
- [7] G. Hagerman, B. Polagye, R. Bedard, M. Previstic, Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices, Electric Power Research Institute, EPRI-TP-001 NA, 2006.
- [8] M. Grabb, E. Lalander, S. Lundin, M. Leijon, A review of the tidal current energy resource in Norway, *Renewable and Sustainable Energy Reviews*, 13 (2009) 1898-1909.
- [9] R.H. Charlier, Sustainable co-generation from the tides: A review, *Renewable & Sustainable Energy Reviews*, 7 (2003) 187-213.
- [10] J. Callaghan, *Future Marine Energy - Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy*, The Carbon Trust, London, 2006.
- [11] A. Zervos, C. Lins, J. Math, RE-thinking 2050 - A 100% Renewable Energy Vision for the European Union, ERFC European Renewable Energy Council, Brussels, 2010.
- [12] T. Khan, G. Bhuyan, *Ocean Energy: Global Technology Development Status*, Powertech Labs, Surrey, 2009.
- [13] E. Friberg, *Current Power Resource Assessment*, Angströmlaboratoriet, Uppsala University, Uppsala, 2006.

- [14] M. Grabbe, Marine Current Energy Conversion - Resource and Technology, Department of Engineering Sciences, Uppsala University, Uppsala, 2008.
- [15] M. Leijon, H. Bernhoff, M. Berg, O. Ågren, Economical considerations of renewable electric energy production--especially development of wave energy, *Renewable Energy*, 28 (2003) 1201-1209.
- [16] R.H. Charlier, Ocean alternative energy - The view from China - 'small is beautiful', *Renewable & Sustainable Energy Reviews*, 5 (2001) 403-409.
- [17] S.D. Anderson, M. Nogueira, F.L. Tavares Marques, Tide-generated energy at the Amazon estuary: The use of traditional technology to support modern development, *Renewable Energy*, 3 (1993) 271-278.
- [18] M.F. Gómez, S. Silveira, Rural electrification of the Brazilian Amazon - Achievements and lessons, *Energy Policy*, 38 (2010) 6251-6260.
- [19] H. Ahlborg, L. Hammar, Drivers and barriers to rural electrification in Tanzania and Mozambique - grid extension, off-grid and renewable energy sources, *World Renewable Energy Congress*, Linköping, 2011.
- [20] EWURA, Appendix 2A Detailed tariff calculations for year 2011 for the sale of electricity to the main grid in Tanzania under standardized small power purchase agreements in Tanzania, Energy and Water Regulatory Authority, Dar es Salaam. Available at: <http://www.ewura.go.tz/pdf/SPPT/>, June 2011.
- [21] EWURA, Appendix 2B Detailed tariff calculations for year 2011 for the sale of electricity to the mini-grids in Tanzania under standardized small power purchase agreements in Tanzania, Energy and Water Regulatory Authority, Dar es Salaam. Available at: <http://www.ewura.go.tz/pdf/SPPT/>, June 2011.
- [22] R. Holland, L. Perera, T. Sanchez, R. Wilkinson, Decentralised rural electrification: Critical success factors and experiences of an NGO, *Refocus*, 2 (2001) 28-31.
- [23] A. Chaurey, T.C. Kandpal, A techno-economic comparison of rural electrification based on solar home systems and PV microgrids, *Energy Policy*, 38 (2010) 3118-3129.
- [24] M.J. Khan, M.T. Iqbal, J.E. Quaicoe, River current energy conversion systems: Progress, prospects and challenges, *Renewable & Sustainable Energy Reviews*, 12 (2008) 2177-2193.
- [25] D. Li, S. Wang, P. Yuan, An overview of development of tidal current in China: Energy resource, conversion technology and opportunities, *Renewable and Sustainable Energy Reviews*, 14 (2010) 2896-2905.
- [26] L.S. Blunden, A.S. Bahaj, Initial evaluation of tidal stream energy resources at Portland Bill, UK, *Renewable Energy*, 31 (2006) 121-132.
- [27] Y.S. Lim, S.L. Koh, Analytical assessments on the potential of harnessing tidal currents for electricity generation in Malaysia, *Renewable Energy*, 35 (2010) 1024-1032.
- [28] ESRU, Marine Current Resource and Technology Methodology, University of Strathclyde, 2004.
- [29] Z. Kowalik, Tide distribution and tapping into tidal energy, *Oceanologia*, 46 (2004) 291-331.
- [30] L.S. Blunden, A.S. Bahaj, Tidal energy resource assessment for tidal stream generators, *Proc. IMechE*, 221 (2007) 137-146.
- [31] I.G. Bryden, S.J. Couch, ME1--marine energy extraction: tidal resource analysis, *Renewable Energy*, 31 (2006) 133-139.
- [32] F. Zabihiyan, A.S. Fung, Review of marine renewable energies: Case study of Iran, *Renewable & Sustainable Energy Reviews*, 15 (2011) 2461-2474.
- [33] A.M. Gorlov, *Tidal Energy*, Academic Press, 2001.
- [34] M.J. Khan, G. Bhuyan, M.T. Iqbal, J.E. Quaicoe, Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review, *Applied Energy*, 86 (2009) 1823-1835.
- [35] B. Kirke, Developments in ducted water current turbines. Available at: <http://www.cyberiad.net/>, October 2010.
- [36] D.K.A. Barnes, M. Whittington, Biomechanics and mass mortality of erect bryozoans on a coral reef, *J. Mar. Biol. Ass. U.K.*, 79 (1999) 745-749.
- [37] A.F. Mavume, Throughflow in Ponta Torres strait - Inhaca, Mozambique - in relation to sea level differences, tides, winds and wave set-up, Department of Oceanography, Gothenburg University, Gothenburg, 2000.
- [38] A. Mavume, B. Malauene, A. Silva, E. Mulchande, O. Pereira, A. Guissamulo, Dugongo Ecology and Bazaruto Habitat Mapping Project 2004-2005, UEM-DF Oceanography Team 2005, Maputo, 2005.
- [39] P.L. Fraenkel, Power from marine currents, *Proceedings of the Institution of Mechanical Engineers*, 216 (2002) 1-14.
- [40] V.F. Saide, Tides, Circulation and Water Masses in Maputo Bay, Department of Oceanography, Gothenburg University, Gothenburg, 2000.
- [41] H. Blennow, Method for Rural Load Estimations - a case study in Tanzania, Department of Heat and Power Engineering, Lund Institute of Technology, Lund, 2004.
- [42] M. Gustavsson, With time comes increased loads--An analysis of solar home system use in Lundazi, Zambia, *Renewable Energy*, 32 (2007) 796-813.
- [43] N.P.A. Smith, Key factors for the success of village hydro-electric programmes, *Renewable Energy*, 5 (1994) 1453-1460.
- [44] G.J. Jones, G. Thompson, Renewable energy for African development, *Solar Energy*, 58 (1996) 103-109.
- [45] A. Brew-Hammond, F. Kemausuor, Energy for all in Africa -- to be or not to be?!, *Current Opinion in Environmental Sustainability*, 1 (2009) 83-88.
- [46] T. Urnee, D. Harries, A. Schlapfer, Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific, *Renewable Energy*, 34 (2009) 354-357.
- [47] L. Hammar, J. Ehnberg, M. Gullström, S. Molander, Ocean energy in combination with land-based renewable energy sources: appropriate technology for smaller electricity grids in Africa?, 8th European Wave and Tidal Energy Conference, Uppsala, 2009.
- [48] R. Inger, M.J. Attrill, S. Bearhop, A.C. Broderick, W. James Grecian, D.J. Hodgson, C. Mills, E. Sheehan, S.C. Votier, M.J. Witt, B.J. Godley, Marine renewable energy: potential benefits to biodiversity? An urgent call for research, *Journal of Applied Ecology*, 46 (2009) 1145-1153.

PAPER III

Ocean energy in combination with land-based renewable energy sources: appropriate technology for smaller electricity grids in Africa?

L. Hammar¹, J. Ehnberg², M. Gullström³, S. Molander¹

¹Chalmers University of Technology,
Environmental System Analysis,
SE-412 96 Göteborg,
Sweden.

²University West,
Engineering Science,
SE-461 86 Trollhättan,
Sweden.

³Stockholm University,
Systems Ecology,
SE-106 91 Stockholm,
Sweden

Abstract

The rapid development within ocean energy includes a numerous set of different energy converters differentiated both regarding technical scale and resource requirements. While many of the developers focus on resource hot-spots and commercialization in industrial countries, some technologies may benefit from shifting into niche markets in developing countries. Prerequisites for future sustainable implementations of small-scale ocean energy for electrification of rural communities in low latitude developing regions are reviewed using African countries as case study. To meet the ubiquitous need of power generation at village level in remote areas renewable energy systems, often based on solar photovoltaic, are becoming more frequently implemented. Despite choice of energy source, several small rather than fewer large generators may be preferable since development of distribution grids is generally very slow. This paper discusses ocean energy converter concepts in the perspective of appropriate technology for developing country implementation, and its potential benefits of combination with other sources in small grids.

Keywords: Developing countries, renewable energy, small-scale, ocean energy, electrification

1 Introduction

The harnessing of renewable energy sources (RES) has been pointed out as necessary for a sustainable

development since threats to climate change must be met simultaneously with the provision of reasonable amounts of energy to developing societies. Furthermore the concomitant limitations of finance, competence and institutional support severely affect the spread of RES-based technologies (RET) for electrification in rural areas of developing countries [1].

There are several ways to secure energy availability in rural areas of developing countries but the authors believe that grid extension is, at least at current speed, not a suitable solution. Small autonomous systems are therefore an appropriate first step to secure the availability of energy. However, small autonomous systems require a variety of sources to secure continuation in availability [2]. Small-scale energy systems may also be of preference from an environmental perspective since ecological values are of great importance in communities where local population are certainly dependent of ecosystem services.

In order to obtain an integrated assessment of social, technical and ecological prerequisites and consequences for RES-based electrification in South-East Africa, a region with reasonably availability of RES, a huge need for electric power and a very low rate of electrification, the STEEP-RES (Socio-Technical-Ecological Evaluation of Potential Renewable Energy Sources) research program has been initiated. In collaboration with local research institutions the program further includes a comparative assessment of RES availability in the region.

As a result of governmental and donor organizations, and with the support of CDM (Clean Development Mechanism) or subsequent post-Kyoto-protocol programs, appropriate RET are offered an

alternative market in developing countries [3,4]. If RET, including ocean energies, can be found viable not only on large scale national level but also for rural electrification purposes on small scale community level, the market for appropriate technologies may become vast.

As an example, global overviews of the tidal energy potential [5], shows substantial tidal ranges in several semidiurnal tides is found in north western Latin America (e.g. Colombia, Panama, Ecuador), in southern Argentina, in East Asia (e.g. Philippines) and in East Africa (Mozambique, Tanzania, Madagascar). Potential for high diurnal tides is found in South East Asia (China, Indonesia). Significant wave energy Chile, Indonesia and several remote oceanic islands [5]. The long coastlines of South-East Africa are characterized by a large and geographically dispersed population in need of electrical power, along with a significant, though not immense, tidal range. In contrast, South-West Africa holds a considerable exposure to waves.

This paper gives a brief introduction to the challenges posed by the preconditions of developing technologies from a developing country perspective.

2 Special preconditions of developing regions

Underdeveloped business organisation may lead to a lack of locally available spare parts [2,6]. Insufficient infrastructure also complicates transport of produced electricity. Extension of the national grid is a slow and very costly process [4]; therefore local production of electricity can be a viable option. Since power systems in small self-contained power grids are autonomous the generation reliability has to be thoroughly considered and the combination of different RET's for electricity generation may be important for the total availability and reliability of the autonomous grid. E.g. wind and wave energy systems are weather dependent and may be considered unreliable as solitary sources. Solar and but the given null-production hours has to be deeply considered if being used in solitary systems.

Thief and vandalism are unfortunately also factors to consider when choosing and designing electric power systems [6,8]. The problem is so large in Tanzania that rewards have been launched to reduce it [14]. Among means to prevent vandalism and theft are social constructions even for light implementation of RET [6]. For instance, in Tanzania and Mozambique site specific by independent researchers and by the national meteorological institutes. However, the measurements often lack continuity, are of low geographical resolution [6], and/or cover only a short period of time [9]. As an example, even though Mozambique apparently have a high tidal range, a good coastal wind climate [10], and a promising insolation [11], consequently come in conflict with local livelihoods, use of the resource for electricity production may

be considered unviable as solitary sources. Solar and wave energy systems are weather dependent and may be considered unreliable as solitary sources. Solar and but the given null-production hours has to be deeply considered if being used in solitary systems.

Thief and vandalism are unfortunately also factors to consider when choosing and designing electric power systems [6,8]. The problem is so large in Tanzania that rewards have been launched to reduce it [14]. Among means to prevent vandalism and theft are social constructions even for light implementation of RET [6]. For instance, in Tanzania and Mozambique site specific by independent researchers and by the national meteorological institutes. However, the measurements often lack continuity, are of low geographical resolution [6], and/or cover only a short period of time [9]. As an example, even though Mozambique apparently have a high tidal range, a good coastal wind climate [10], and a promising insolation [11], consequently come in conflict with local livelihoods, use of the resource for electricity production may

be considered unviable as solitary sources. Solar and wave energy systems are weather dependent and may be considered unreliable as solitary sources. Solar and but the given null-production hours has to be deeply considered if being used in solitary systems.

Thief and vandalism are unfortunately also factors to consider when choosing and designing electric power systems [6,8]. The problem is so large in Tanzania that rewards have been launched to reduce it [14]. Among means to prevent vandalism and theft are social constructions even for light implementation of RET [6]. For instance, in Tanzania and Mozambique site specific by independent researchers and by the national meteorological institutes. However, the measurements often lack continuity, are of low geographical resolution [6], and/or cover only a short period of time [9]. As an example, even though Mozambique apparently have a high tidal range, a good coastal wind climate [10], and a promising insolation [11], consequently come in conflict with local livelihoods, use of the resource for electricity production may

be considered unviable as solitary sources. Solar and wave energy systems are weather dependent and may be considered unreliable as solitary sources. Solar and but the given null-production hours has to be deeply considered if being used in solitary systems.

e.g. fishery. Tidal barriers may also impact local marine and estuarine ecosystems, posing risks for e.g. bird diversity.

3 Criteria of appropriate technology

The severity of these implementation obstacles can be reduced by the use of "appropriate technology" - a technology that is chosen or adapted to suite local specific requirements in terms of simplicity, robustness, competence of personnel, effect dimension, ecological impacts, social acceptability and institutional support.

For employment of small-scale renewable energy in remote areas of developing countries appropriate technologies may imply electricity converters with no need for transported fuel (which is the case for renewable energy technologies in general), low installation efforts, and daily operation and maintenance duties that can be performed by personnel with very basic skills. Further, it is beneficial with technical systems that do not contain essential parts possible to punch. To secure availability of the energy the source should rather be a power source than an energy source. In many regions of developing regions it is also of certain importance that the resource extraction does not infer with local livelihood ecosystems.

Appropriate technology will hardly be a large high-effect installation, but a scalable solution on the lower range of installed effect. However, in order to enhance chances of successful technology transfer it is indicated that the generated electricity should not be too low either, as in the case of solar home systems [15].

In this section different solutions on renewable energy with a focus on ocean energy will be discussed from the appropriate technology perspective.

Wave energy and tidal energy, including tidal stream and tidal potential, are ocean energy sources which may possess a potential for employment in the context of rural electrification in developing countries. Here, thermal exchangers are excluded since these are bound to deep waters and large-scale employments. We argue that appropriate technology may preferably be energy systems employed on near-shore sites, which facilitates installation, ease maintenance and reduce costs of submarine cables. Moreover, a common obstacle for small-scale ocean energy is the sensitivity to extreme weather conditions; geographical regions with cyclone climate may consequently be directly inappropriate.

Wave energy Among the approximately 100 identified wave energy prototypes [16], most concepts allow some kind of floating device, which is firmly anchored to follow the movement of the surface. Either coastal water waves or

Shimoy (JHC Engineering Business Ltd). Examples on developing prototypes are the floating *Kobold Turbine* (Ponté d'Arche) and the *Ocean Turbine* (Blue Energy) and the fully submerged *Shimoy* (JHC Engineering Business Ltd).

ocean swell is utilized. Electricity is created by compressing flow to propel the generator. Examples are attenuator concepts, like *Pelamis* (Pelamis wave Power) [17], *Swell Fuel* (Swell Fuel) and *Ocean* (Green Ocean energy Ltd), or the more common point absorber concepts like *Aquadrop* (Finavera Renewables), *WET EnGen* (Wave energy Technologies Inc.) and *Seahorse WEC* (Seabased AB) [18] where the generator is submerged. Also several oscillating water column (OWC) devices use a floating concept in opposite, oscillating wave surge converters like *WaveRoller* (AW-EnEnergy) [19], *Oyster* (Aquamarine Power) and *BuoyWave* (BuoyWave Systems).

Submerged technologies may have benefits from works fully submerged in shallow water.

The offshore possibility of installation directly from sea, reducing land transports, is a strong advantage in areas with low infrastructure.

Some oscillating water column devices, like the *Pico* (Pico Energy), are installed on land utilizing energy from the breakwater as the incoming waves compress locked-in air that drive a generator. This concept may be more difficult to install in remote areas, but gain significant benefits from facilitated maintenance.

Finally and evidently, the wave energy generation reliability is low in most near-shore locations since the source is weather (wind) dependent. As remote developing regions often lack access to a larger electricity grid this implication becomes large, and motivates use of multiple sources (e.g. solar energy).

Utilization of tidal energy will give higher generation reliability due to its regularity which may be certainly attractive for remote developing regions (or islands) with substantial tides. The principle for tidal stream converters have similarities to that of wind power, but operating below the water surface where much lower speeds can be utilized due to the higher power density of water compared to air [20]. Among about 50 identified prototypes [16] different concepts are used, like horizontal axis turbines (including venturi effect), vertical axis turbines, and oscillating hydrofoils, to generate electricity at substantial water currents (in Examples on developing prototypes are the floating *Kobold Turbine* (Ponté d'Arche) and the *Ocean Turbine* (Blue Energy) and the fully submerged *Shimoy* (JHC Engineering Business Ltd).

Examples on developing prototypes are the floating *Kobold Turbine* (Ponté d'Arche) and the *Ocean Turbine* (Blue Energy) and the fully submerged *Shimoy* (JHC Engineering Business Ltd).

Examples on developing prototypes are the floating *Kobold Turbine* (Ponté d'Arche) and the *Ocean Turbine* (Blue Energy) and the fully submerged *Shimoy* (JHC Engineering Business Ltd).

Additionally, several large scale devices are piled to the sea floor.

The remote developing region issues of submerged or offshore tidal energy are similar as for wave energy generators, with most importantly complications of maintenance but also benefits from possible sea-based installations.

Another approach of tidal energy is to erect an enclosure, independent or in conjunction with natural rock, which is filled during flood and emptied slowly during ebb tide, allowing water to pass through generators. The same system can be arranged to let water pass through generators on the inflow, consequently producing electricity during tidal flow in both directions. This technology concept has previously been used only for large scale installations, enclosing entire bays or river mouths, which entails large environmental effects from water allocation [9]. A modern solution to this is approaches of smaller "tidal lagoons" rather than barrages, as presented by Tidal Electric which is currently projecting a 60 MW lagoon in British waters but also argues for scalability down to installations on kW levels, which may be more appropriate for meeting power demands and ecological sensitivity of coastal developing regions. This concept can be implemented on intertidal flats or at natural rock and include few moving parts, which is favourable due to maintenance. The technology of the turbines is rather mature and has in principle been in service since the 1960s [21]. A setback for remote locations is the effort consuming construction of the impoundment, even though natural rock can serve as part of the wall.

Moreover, Woodshed Technologies has suggested a tidal energy approach, *TidalDelay*, where the potential energy of water level differences on opposite sides of a narrow peninsula is tapped by turbines installed in connective pipes. This concept has several advantages as being land based and relatively easy constructed and maintained, however appropriate sites may be very sparse. The predictability of tidal energy is an advantage in comparison with weather dependent sources and short term storage of energy may work to ease synchronization with load in solitary grids. However, multiple source grids will be beneficial also for tidal energy systems.

Land-based RES

Land-based renewable energy technologies are generally more mature and are increasingly discussed from a developing country perspective. Since this paper only discusses small-scale electricity sources geothermal energy as well as thermal solar power systems is not further considered. Bio-energy electricity conversion may be of interest where the harvest can be done locally and does not cause deforestation or compete with food production.

Wind power, as being a rather mature energy source, is of interest from a developing country perspective if wind speeds are prominent all year round. However, there has not been any substantial boom for wind power in many developing countries, with true

exceptions of economically expanding countries like China and India. Lack of local responsibility and competence for wind mill maintenance at community level [12], and lack of successful measures against theft and vandalism [14], has been reported as major impediments for successful technology transfer in Tanzania. Another concern with wind energy is the stochastic behaviour of power production, an issue that to some degree can be counteracted by using designs that utilises lower wind speeds to a higher extent, as proposed by Khan *et al.* [22]. Another interesting solution for wind energy is to combine it with other more regularly used sources like solar [2].

Solar power can be seen as a very promising solution since the resource is available in many developing countries of low latitudes [23] and the generation is often regular. Subtropical regions may offer certainly good conditions for solar power while clouds are very frequent in coastal tropical regions, somehow reducing its potential here. The systems can be scaled to any size and to be placed out of reach to prevent theft and vandalism. Disadvantages with smaller solar photovoltaic systems are the relatively low effects obtainable and the installation costs.

Need of adaption

In Table 1 the need of adaption before implementation of above discussed energy conversion technologies are summarized. The table highlights discussed needs of technical adaptation associated with technology transfer in developing countries; however this discussion does not include the economic and social prerequisites for technology absorption.

Table 1. The table summarize how different concepts of discussed RET meet issues of appropriate technology from a developing country perspective. The magnitude of need for adaption is estimated as Adaption Needed (AN) and Minor Adaption Needed (MAN). No Specific (NS) adaption needed indicates that the authors cannot foresee particular technical adaption for implementation in developing countries. For the land-based energy conversion systems the water allocation is not relevant (nr).

	Generation reliability	Installation	Transport	Maintenance	Vandalism and theft	Water allocation
Wave Energy; submerged	MAN	AN	AN	NS	NS	
Wave Energy; surface	MAN	MAN	MAN	MAN	MAN	MAN
Wave Energy; land	MAN	MAN	MAN	AN	AN	MAN
Tidal Stream; submerged	NS	AN	AN	NS	NS	
Tidal Stream; surface	NS	MAN	MAN	MAN	MAN	MAN
Tidal (range) Potential	NS	AN	MAN	MAN	MAN	AN
Wind Power	MAN	MAN	MAN	AN	nr	
Solar Power	MAN	NS	MAN	MAN	nr	

5 Combinations of appropriate RES

As emphasized in Table 1 the weather dependent RES offer complications with generation reliability and therefore a combination of sources are needed. Therefore autonomous systems are normally combined with sources of high generation reliability, for example a diesel generator [24]. However, during later years other combinations have been developed due to technical progress, like combinations with fuel-cells [25]. Here, technologies are still in under development. When utilizing tidal energy the availability is of concern. Electricity from the predictable tide can be used to supplement parallel technologies with lower generation reliability; the total reliability will then increase significantly as shown by Ehnberg [2].

The control of a system with a combination of sources is more complicated than if only a single source is used. The control method also needs to be adapted to the combination of sources in order to maximise the energy use of the system. In case of combinations of sources with low generation reliability such as wave or wind power, or technologies without storage possibilities, it has been shown that a load based control system can be favourable [2]. In the case of tidal potential power (e.g. the "tidal lagoon" concept) the built-in storage in the lagoon can be used like storage as in hydro power systems. However, a significant difference is that the water can only be stored until the next flood when unexploited potential has to be wasted to create a new, reverse, potential. The relatively long (hours) lag time between flood and ebb tide, like other sources with variable generation, motivates that also this control method benefits from combination with flexible industrial activity in order to maximise the use of the installation and minimise the problem with availability.

6 Conclusions

Even though the ocean energy technologies are mainly being developed for the industrialized part of the world, some concepts are likely to benefit from further adaption towards the market of developing countries. This way of rural electrification can be supported by CDM or subsequent post-Kyoto-protocol programs.

Installations of ocean energy conversions systems will probably be most interesting as combinations with more mature land-based technologies like solar, in order to increase the generation reliability. The regular tide makes tidal energy conversion systems a certainly interesting component for autonomous power systems based renewable in developing regions, especially for the aspect of generation reliability. However, difficulties on maintenance are of great importance and must, together with social acceptance and ecological considerations, be addressed thoroughly in parallel to any system design.

Furthermore, it is of importance that RET-concepts are scalable, in terms of installed power, in order to be appropriate for markets covering large spans of

demand, which can be expected in developing countries.

Acknowledgements

The authors would like to thank the Futura Foundation for financial support.

References

- [1] Murphy, J. T. (2001). "Making the energy transition in rural east Africa: Is leapfrogging an alternative?" *Technological Forecasting and Social Change* 68(2): 173-193
- [2] J. Ehnberg, *Autonomous Power Systems based on renewable - on generation reliability and system control*, PhD thesis, Chalmers University of Technology, Göteborg, 2007.
- [3] H. Doukas, C. Karakosta, J. Psarras. RES technology transfer within the new climate regime: A "helicopter" view under the CDM. *Renewable and Sustainable Energy Reviews* 13: 1138-1143, 2009.
- [4] N. Duic, L.M. Alves, F. Chen, M. de Graca Carvalho. Potential of Kyoto Protocol Clean Development Mechanism in transfer of clean energy technologies to Small Island Developing States: case study of Cape Verde. *Renewable and Sustainable Energy Reviews* 7: 83-98, 2003.
- [5] EPRI Electric Power Research Institute. Ocean Tidal and Wave Energy - Renewable Energy Technical Assessment Guide. Report, 2005.
- [6] M. Sheya and S. Mushi. The state of renewable energy harnessing in Tanzania, *Applied Energy*, 65: 257-271, 2000.
- [7] R. Kadigi et al. Water for irrigation or hydropower generation? - Complex question regarding water allocation in Tanzania, *Agricultural water management*, 95: 984-992, 2008.
- [8] J. Ehnberg, Study trip to Tanzania in February 2005. Technical report, Department of Energy and Environment, Chalmers University of Technology, Sweden, 2006.
- [9] A. Dubi, Tidal Power Potential in the submerged Channels of Dar es Salaam Coastal Waters, *Western Indian Ocean J. Mar. Sci.*, 5: 95-104, 2006.
- [10] B.C Cuamba, R. Uthui, M.L. Chenene et al., Identification of areas with likely good wind regimes for energy applications in Mozambique, Eduardo Mondlane University, Unpublished report.
- [11] B.C Cuamba, M.L. Chenene, G. Mahumane et al., Solar energy resources assessment in Mozambique, Eduardo Mondlane University, Unpublished report.
- [12] STEEP-RES, Field report on renewable energy discussions in East Africa, Chalmers University of Technology, 2009.

- [13] M Gustavsson, *Solar Energy for a Brighter Life - A Case Study of Rural Electrification through Solar Photovoltaic Technology in the Eastern Province, Zambia*, Dissertation, University of Gothenburg, 2008.
- [14] Tanesco Ltd, *TANESCO LOSES TSH 796 MILLION OIL TO VANDALS* [Electronic] Dar-es-salaam Available: <<http://www.tanesco.com>> [2009-04-13]
- [15] J. T. Murphy, Making the energy transition in rural East Africa: Is leapfrogging an alternative? *Technological Forecasting and Social Change* 68: 173-193, 2001.
- [16] EMEC The European Marine Energy Centre Ltd. Available <<http://www.emec.org.uk>> [2009-04-19]
- [17] D. Kerr, Marine Energy, *Phil. Trans. R. Soc. A*, 365: 971-992, 2007.
- [18] M. Leijon *et al.*, An electrical approach to wave energy conversion, *Renewable Energy*, 31: 1309-1319, 2006.
- [19] A.W-energy, WaveRoller Concept, [Electronic] Vantaa Available: <<http://www.aw-energy.com>> [2009-04-19]

- [20] M. Khan, River current energy conversion systems: Progress, prospects and challenges, *Renewable and Sustainable Energy Reviews*, 12: 2177-2193, 2008.
- [21] I. Usachev *et al.*, Performance control of a marine power plant in the Russian arctic coast and prospects for the wide - scale use of tidal energy, *Power Technology and Engineering*, 38: 188-193, 2004.
- [22] A. Khan *et al.* On adapting a Small PM Wind Generator for a Maithbade, High Solidity Wind Turbine, *IEEE Transaction on energy conversion*, 20: 685-692, 2005.
- [23] L. Dibaba *et al.*, Solar radiation climate in Africa, *Solar Energy*, 76: 733-744, 2004.
- [24] N. Lipman, 'Overview of Wind/diesel systems', *Renewable Energy*, 5: 595-617, 1994.
- [25] E. Kassemis *et al.*, 'Optimization of a wind-power fuel-cell hybrid system in a autonomous electrical network environment', *Renewable Energy*, 32: 57-79, 2007.

Drivers and barriers to rural electrification in Tanzania and Mozambique – grid extension, off-grid and renewable energy sources

Helene Ahlborg^{1*}, Linus Hammar²

^{1,2}Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Sweden

*Corresponding author. Tel: +46 31 7728601, E-mail: helene.ahlborg@chalmers.se

Abstract: Mozambique and Tanzania are countries with very low rural electrification rates – far below 5 % percent of the rural population use electricity. The pace of rural grid electrification is slow and for most remote areas access to the national electricity grids will not occur within a foreseeable future. Off-grid (decentralized) electricity grids are seen as a complement and fore-runner to the national grid, making electricity available many years in advance and creating demand and a customer base. Most off-grid systems are supplied by diesel generators which entail unreliable and costly electricity. Alternative off-grid energy sources exist in the region, such as biofuels, wind, micro-hydro and solar PV, but there are significant barriers to adoption, adaptation and diffusion of such RE-based technologies. In this study, the specific drivers and barriers for rural electrification and off-grid solutions in both countries are explored across a stakeholder spectrum. It is part of a larger research effort, undertaken in collaboration between Swedish and African researchers from natural, engineering and social sciences, aiming at an interdisciplinary assessment of the potential for an enhanced utilization of available renewable sources in off-grid solutions. By qualitative methodology, data was collected in semi-structured stakeholder interviews carried out with ten national level energy sector actors. Findings illustrate country-specific institutional, financial and poverty-related drivers and barriers to grid and off-grid electrification, as perceived by different energy sector stakeholders.

Keywords: Rural Electrification, Off-grid Systems, Renewable Energy, Africa, Drivers and Barriers

1. Introduction

There is little doubt that access to and use of electricity is a benefit to people, not only in the current electricity-dependent world but also in developing rural areas. While electricity may not bring development on its own it is a highly desired commodity and a prerequisite to rural development in long term perspective [1] [2]. In the first industrial countries massive electrification was initiated in the 1880's, to be completed only decades after the World War II; a huge effort backed by powerful institutions. The challenge is now to spread the same technologies in emerging economies with often very different institutional, cultural and financial conditions. One such region is sub-Saharan Africa where the electrification level is minute – especially in rural areas.

In this study, the current and future prospects for rural electrification (RE) in Mozambique and Tanzania are assessed in terms of drivers and barriers for RE through grid extension and off-grid solutions; based on interviews with key stakeholders from government, international donors, private sector and civil society in both countries carried out during 2010. The aim is to conduct a cross-sector analysis of country specific drivers and barriers to successful RE and use of renewable energy sources (RES) in off-grid systems, as perceived by stakeholders influencing the development in each country. Both countries have very low RE levels and there is a long history of Swedish bilateral partnership within the energy sectors. The analysis reveals important drivers and barriers at national and local level, some of which are not addressed in literature reviewed. The paper starts with a description of current conditions for RE in sub-Saharan Africa. Thereafter, the electricity sub-sectors of Tanzania and Mozambique are outlined followed by a section on method. The results for each country are presented and discussed, followed by conclusions.

is responsible for facilitating RE which is done by supporting applicants (public, NGO or private) with grants for organizational learning and for capital investment (normally covering up to 30% of the project). Other important actors are donors, who provide major parts of the energy budget, NGO's (primarily TATEDO) and international consultants.

1.3. Rural electrification in Mozambique

In Mozambique the electricity generation is heavily dominated by the 2075 MW hydro power station Cahora Bassa, situated in the north western part of the country. Cahora Bassa, a few smaller hydropower stations and a back-up coal power station supply all electricity to the national grid. The lion share of electricity from Cahora Bassa is exported to neighboring countries but transmission lines reach the largest cities and some towns. Since the country is stretching over enormous distances transmission losses are significant and the power supply becomes fragile in the outskirts of the grid. Numerous diesel generators have been allocated to supply smaller and remote districts. In difference to Tanzania the country has endured a long lasting civil war, ended in 1992. Since then the efforts in grid extension have been significant; still the RE level was below 2% in 2007.

EdM (Electricidade de Moçambique) is the governmental utility responsible for electrification (generation, transmission and distribution) in Mozambique, but a restructure is considered. EdM buys most of its distributed electricity from the Cahora Bassa dam to low costs which somewhat complicates competition and introduction of other energy sources. The private sector, however, are free to contribute. EdM carries out RE by extending the national grid and the tariff is regulated by the Ministry of Energy. Another public institution is FUNAE (National Fund for Rural Electrification), founded in 1997 and strongly supported by donors, in practice responsible for rural off-grid electrification mainly using diesel generators and solar PV systems. Like in Tanzania, foreign consultants play an important role both in development of national strategies and project specific planning. In Mozambique very few NGO's are involved in RE.

2. Method

The study was conducted during eight weeks of field work in Tanzania and Mozambique in January-March 2010. By qualitative methodology data were collected through interviews with stakeholders. The interviews addressed six themes: (1) current state of the electricity infrastructure in rural areas; (2) institutional and socioeconomic drivers and barriers to RE; (3) productive uses of electricity; (4) potential for off-grid and renewable energy systems; (5) local participation in electrification processes; and (6) impact from electricity on people's lives. The themes were based on a review [9] of mostly African-related peer-reviewed literature (results presented in Table 2 alongside interview results). The interviews were recorded (unless circumstances made this impossible) as sound files. The interviews were semi-structured, i.e. asking open-ended questions, using an interview guide, and considering the professional experience of the respondent [11]. This paper presents the findings from 17 interviews carried out with government staff, donors, consultants and NGOs. The respondents were selected based on their influence in and experience of RE processes. Some interviews are with two or three respondents at the time. Our analytical strategy is based on theoretical propositions [12] and the concepts of 'drivers' and 'barriers', which are commonly found in the management literature, but are also commonly used by stakeholders in the field, as to signify factors that enhance or hinder the wished-for development.

1.1. Prerequisites for rural electrification in sub-Saharan Africa

In any country the construction of electric grids to distribute power in rural areas is an infrastructure assignment carrying huge expenses, not less so in most African countries where existing infrastructure is rudimentary. In Africa and elsewhere, RE has largely been the responsibility of the public sector, which in the African context generally implies a large influence from donors. In comparison with industrial countries and own ambitions, RE in Africa has been progressing at a slow pace. In order to speed up the process and involve the private sector as encouraged by the World Bank, many African countries have in later years taken on energy sector reforms, strategies which have yet not shown intended results [3]. The large distances and low incomes make distribution expensive and rural customers financially unattractive to private sector investors.

Expenses associated with vast distance could be met by decentralized grids in wait of full grid coverage. Such off-grid approaches for supplying electricity in remote areas are frequently powered by diesel generators which are dependent on fuel transports for operation, and generate a comparatively higher running cost. An alternative to diesel powered off-grid are available renewable energy sources (RES). In sub-Saharan Africa the potential of RES is high [4] and particularly micro hydro power and solar photovoltaic (PV) have been utilized so far. Due to the low population density and geographical distances, RES are often the least-cost alternative and financing instruments like the Clean Development Mechanism can become an important driver for RES in both countries [4, 5]. The extensive pan-African literature covers progress and constraints of such RES based off-grid implementations [6] [7] [8]. Moreover, rural households which have resulted in an internal market for these technologies in some countries. The SHS trend is accompanied by a substantial impact assessment literature. Rural area energy transition is not unproblematic and several barriers have been identified – both regarding RE in general and regarding the use of RES in off-grid in particular. An earlier literature review [9] identified barriers within the following areas: institutions and stakeholders performance; economy- and finance; social dimensions; technical system and its management; technology diffusion and adaptation; and rural infrastructure.

1.2. Rural electrification in Tanzania

Tanzania's current electricity generation relies heavily on hydropower; secondary sources are domestic natural gas and imported oil. In 2008 the total power generation capacity was 1100 MW. The transmission grid covers a minor part of the country leaving out most areas, particularly western and southern regions. District capitals and other important centers are supplied by diesel generators. The RE level is currently 2% (2009). There is an outspoken intention to utilize the prominent availability of RES, in particular for enhancing RE [10]. Still, there is little use of RES for electricity generation and only 13 % of the disbursed budget 2008/2009 was used for RE and RES altogether (corresponding to 1/3 of what was used for the gas and petroleum sector).

The Tanzanian power subsector, under the Ministry of Energy and Minerals, is dominated by the public agency Tanesco (Tanzania Electric Supply Company). An energy sector reform has taken place during the last decade, leading to the enactment of the Electricity Act in 2008 [10]; private sector is now encouraged to take an active role within the sector and a regulatory oversight of the tariff system is ensured by the EWURA (Energy and Water Utilities Regulatory Authority), established in 2006. The responsibility of RE has been transferred from TANESCO to the Rural Energy Agency, REA, which became operational in 2007. REA

The interviews have been transcribed and then analysed using the Atlas.ti software for qualitative data analysis. Each interview is read through and then all meaning units (quotations) are sorted into subcategories (e.g. "communication problems"), that are part of categories (e.g. "barriers for RE") which are in turn related to the themes. This type of analysis combines a deductive analysis (categories are based on the themes of interest) with inductive analysis (subcategories emerge from the material) in an iterative process [11]. The software then allows for analysis of e.g. specific categories, subcategories and Boolean queries. The result is a cross-sector mapping allowing for comparison between various perspectives, organizations and between countries.

Some methodological weaknesses should be pointed out. First and foremost, the analysis is limited in scope both in terms of number of respondents and time allocated in each interview. The respondents are in general very knowledgeable in their area and much more can be learnt from each stakeholder. For practical reasons, only one interview was held with each respondent, implying that the analysis reflects what stakeholders found relevant at a specific point in time. However, the format of semi-structured interviews allows for respondents to reflect on their own answers and bring up additional aspects even if not asked for. Second, there is always a risk of misunderstandings, due to lacking language skills. Interviews were held in English and translated by local interpreter when necessary. Further, information given must be assessed critically as respondents may lack knowledge or hold subjective perceptions that are inaccurate in some areas. Such weaknesses are addressed through triangulation of findings. It also matters if there are sensitive issues to which respondents are unwilling to answer. The question of biases in interviews, the concepts of reliability and validity (coming from quantitative science) are discussed in length in literature and take on a slightly different meaning for this type of analysis [11]. In this study, trustworthiness of results is sought by two researchers searching for inconsistencies and comparing findings to existing literature.

3. Results

3.1. Indicated drivers and barriers for rural electrification

Results of identified barriers and drivers are shown in Table 1 and 2 respectively, and discussed in section 4. The respondents' reflections regarding the potential for renewable energies are not included in the tables but presented in the following section (3.2.).

3.2. Respondents' reflections regarding the potential of renewable energy sources

Among the renewable energy sources known to be available in the region micro/pico hydro power were evidently the source most appreciated among respondents. In Mozambique most respondents and in particular the EdM were very enthusiastic about the potential of micro scale hydro for off-grid applications (notably, no larger expansion of hydro power have been undertaken since colonial time in the country). Apart from hydro power EdM showed little interest for renewable sources. In Tanzania the potential exploitation of new hydro power resources, including micro scale, was greatly advocated by Consultant A who also stated that hydro power expansion in Tanzania are being successfully counteracted by the gas lobby. Hydro power has the strong benefit of higher capacity than e.g. solar PV while the flipside of the coin are the seasonal droughts that in particular have affected Tanzania. Regarding wind power there were little support in both countries, with skepticism related to costs and fluctuations. However, wind power got some support from Tanesco's research division. Solar PV is used for off-grid electrification in both countries still it was referred to as generally expensive and of low productive use. Regarding geothermal energy conversion Consultant A reported that a previous assessment has indicated good resources but low political interest.

Table 1. Identified barriers or constraints to successful RE in general (B) and to off-grid electrification in particular (b) extracted from stakeholder interviews and Africa-related literature (L). Tanzania: 1=Tanesco, 2=REA, 3=TaTEDO, 4=Donor, 5=Consultant A, Mozambique: 6=EdM, 7=FUNAE, 8=Donor, 9=Consultant B, 10=Consultant C. Number of interviews: i-iii.

Identified barrier	Source										
	L	1	2	3	4	5	6	7	8	9	10
	iii	ii	i		ii	i	iii	ii	i	i	i
<i>Institutions and stakeholder performance</i>											
Low institutional quality	B				B	B	B				B
Inadequate planning capacity	B	B			B	B			B		
Organizational structure and strategies	B					B					
Lack of co-investments (rural develop.)	B					B					
Lack of private sector involvement	B		b		B						
Incompatible donor policies						b					
Top-down management in energy sector					b	B	B	B			
<i>Economy and finance</i>											
Tariff system and connection fees	B		b		B	B					
Subsidies	B		b		B						
Insufficient rural financial institutions	B		b		B						
Poor rural market and low productive use	B	B	b		b		B		B	B	B
Admin. costs in small off-grid systems	B									B	
Compensation (in land acquisition)		B									
Lack of consistency between RE projects		B									
High costs of diesel		B		b			b	b		B	b
Donor dependency					B	B	B		B	B	
<i>Social dimensions</i>											
Poverty and low household affordability	B	b	b	b	b	B	B				
Gender issues	B			b							
Problems in local participation and theft	B								B		B
Lack of local engagement						b		b			
Change of mind among costumers								b	B	B	
<i>Technical system and local management</i>											
Lack of access to skilled personnel	B		b							B	b
Weak maintenance culture	B			b		B				B	b
Low capacity of solar PV systems	B					b		b			
Low access to required components	B	B					B	b			
Low generation capacity						B	B		B		B
<i>Technology diffusion and adaption</i>											
Unwillingness of behavioral change	B		b	b							
Users' low awareness of techn. potential	B										
Lack of local entrepreneurship						B	B				
<i>Rural infrastructure</i>											
Scattered population	B	B				B	B	b	B		
Limited rural infrastructure (roads etc.)	B					B					
Long distance transmission							B				B
Traditional houses (electricity prohibited)					b	B					
Devastating cyclones										B	
Nature reserves and national parks						B	B	B			

Table 2. Identified drivers to RE in general (D) and to off-grid electrification in particular (d) extracted from stakeholder interviews. Tanzania: 1=Tanesco, 2=REA, 3=TAJEDO, 4=Donor, 5=Consultant A, Mozambique: 6=EdM, 7=FUNAE, 8=Donor, 9=Consultant B, 10=Consultant C. Number of interviews with each organization: i-iii.

Identified driver	Source	Policy and poverty mitigation ambitions	Governmental policies and subsidies	Political campaigning	Donor push / support	Pushing from individuals in gov. agencies	Private sector involvement	Market incentives	Churches	Social responsibility in private sector	Niche market for certain energy systems	Local demand	Increasing demand (industry, households)	Grass-root organizing	Off-grid RE creates demand for grid ext.	Other	Need of increased sustainability in grid	Promotion of renewable energy / CDM
	1	iii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	2	iii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	3	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	4	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	5	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	6	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	7	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	8	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	9	ii	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d
	10	i	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	d

According to stakeholders, the main drivers for RE in Tanzania are political priorities. Tanzania confronts challenges both at the national and local levels, while no references are made to important actors at the intermediate level. Tanesco is considered the main actor but with major financial and organizational problems. According to donors and consultants, lack a of planning at government level is a main issue, causing inefficient implementation and financing problems – in fact only a minor part (14%) of available funds for energy projects is considered a driver but so far little private investment is taking place in RE. Low return rates, political setting of tariffs and a weak customer base in rural areas makes RE unattractive. Tanesco and REA both use economical potential and productive energy use as indicators for RE planning, still, much would be gained if RE projects would also be accompanied with complementary infrastructure investments according to experienced consultants. Among local barriers, most stakeholders mention poverty and low population density – the latter having huge impact on both distribution and transmission costs. Despite low tariffs (that are financially unviable), rural customers find it difficult to afford connection and subsidies are often used to overcome this barrier. To find a level appropriate both for satisfying consumers and encouraging private sector incentives in the energy sector is difficult. For off-grid, all stakeholders agree that diesel generators are costly and unreliable, but where grid extension is not economically feasible, off-grid solutions are necessary for political goals to be attained. Also in Mozambique, political ambitions are considered the main driver for RE, for social and economical reasons. EdM regard RE as means to slow urbanization, providing better health

care and education, and lower birth rates in rural areas. The lack of industry poses a barrier as RE is not commercially viable and in comparison to Tanzanian agencies the emphasis on prevalent economical potential and productive use are seemingly not used as a strong indicator of where to direct RE. New generation is needed; Mozambique is depending on the large hydro plant Cahora Bassa and long distances leave most of the country without power. Another recognized barrier is that private actors find it hard to compete with Cahora Bassa's cheap electricity. The energy sector is top-down oriented and donor dependency creates problems in budgeting; the budget becomes more of a wish-list than a planning instrument. Diesel generators are very common for small-town electrification and rural off-grid systems have been implemented since colonial times. FUNAE has a major mission carrying out off-grid throughout the country but is still a rather limited and new organization. Off-grid barriers are high costs of diesel, logistics (incl. spare-parts), and communication with consumers due to bad infrastructure. For sustainable off-grid solutions, a technical support system is needed to facilitate maintenance, and most probably there are huge benefits waiting in micro hydro power. Local people's engagement is important but variable, according to FUNAE, impacting off-grid system sustainability. Along the coast, the occurrence of cyclones destroys infrastructure and impedes investments.

In comparison, the two countries face similar challenges with low population densities, weak customer bases, large distances and inadequate infrastructure. While domestic actors regard social demand as an important driver for RE this view is less pronounced by the foreign actors who rather regard the (lack of) economic demand as a barrier. At the national level, both countries rely on external funding for RE, but low institutional capacity and quality – both countries suffer from corruption and politically motivated but economically unviable plans – hinder efficient implementation and use of funds. There is political recognition that grid extension needs to be complemented by off-grid solutions, but the responsible agencies are yet to become fully operational.

The drivers and barriers identified in this study are largely corresponding to those in the literature, as can be seen in Table 2. However, the problems associated with donor dependency and how this impacts budgeting and implementation comes out as important constraints for both countries, which is not discussed in any detail in the RE literature. Institutional weaknesses are often discussed in terms of bad governance, but in Tanzania the lack of correspondence between local realities and donor criteria for RE projects also create institutional barriers. In this study it further found that traditional building techniques (using mud and grass) in rural areas slow down connection rates; a barrier not previously emphasized. All stakeholders turned out to share a view on diesel generators as expensive and unreliable. Here, appropriate RES could assist but the interest among stakeholders is weak. A barrier with certain relevance for the region is the reported lack of complementary services and co-investments to accompany RE. Here, Tanzania seems to have taken more account of recognizing other rural development when carrying out RE. In sum, our results support earlier findings but complement with country-specific drivers and barriers. To be remembered, political ambitions, donor support and an accumulating experience among stakeholders the rate of electrification is keeping up in both studied counties. The methodological weaknesses are primarily due to time constraints and a follow up on sector development over the coming years would improve credibility of finding. This study provides an assessment of drivers and barriers to RE that is broader in scope and more

detailed than earlier writings, and provides an excellent basis for cross-country comparison and in-depth studies for each country. It is also valuable for stakeholders, such as donors, consultants and policy makers, to gain overview of challenges to address.

References

- [1] G. Foley, Rural electrification. The institutional dimension, Utilities Policy, 1992, pp. 283-289
- [2] R. Holland, et al., Decentralised rural electrification : Critical success factors and experiences of an NGO, Refocus 2(6), 2001, pp. 28-31
- [3] N. Wamukonya, Power sector reform in developing countries: mismatched agendas, Energy Policy 31(12), 2003, pp. 1273-1289
- [4] S. Karekezi, Renewables in Africa-meeting the energy needs of the poor, Energy Policy 30(11-12), 2002, pp. 1059-1069
- [5] A.K. Akella, R.P. Saini, and M.P. Sharma, Social, economical and environmental impacts of renewable energy systems, Renewable Energy 34(2), 2009, pp. 390-396
- [6] G.J. Jones and G. Thompson, Renewable energy for African development, Solar Energy 58(1-3), 1996, pp. 103-109
- [7] J.T. Murphy, Making the energy transition in rural east Africa: Is leapfrogging an alternative? Technological Forecasting and Social Change, 68(2), 2001, pp. 173-193
- [8] M. Pigaht and R.J.v.d. Plas, Innovative private micro-hydro power development in Rwanda, Energy Policy 37, 2009, pp. 4753-4760
- [9] H. Ahlborg, et al., A background on social context and renewable energy sources in Mozambique and Tanzania: an initial report from the STEEP-RES project, Chalmers University of Technology, in ESA Report 2008:21, 2008, Göteborg
- [10] MEM, Final report on Joint Energy Sector Reveiw for 2009, Ministry of Energy and Minerals, United republic of Tanzania, 2009, Dar es Salaam
- [11] B. Mikkelsen, Methods for development work and research. A new guide for practitioners, Sage Publications, second edition, 2005, New Dehli/Thousand Oaks/London
- [12] R.K. Yin, Case study research. Design and methods, SAGE Publications, 4 ed., Applied social research methods series, Vol. 5, 2009, Los Angeles

Power sector actors' views on productive use, private sector involvement, and renewable energy in rural electrification of Mozambique and Tanzania

Linus Hammar¹, Helene Ahlborg¹, and Sverker Molander¹

¹Energy and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden

Abstract

Rural electrification can provide social benefits and is an important part of rural development. In the last two decades, developing countries have been undertaking power sector reforms with market liberalization and promotion of private sector involvement in power production and distribution. The option of off-grid electrification based on renewable energy has lately gained attention as a complement to grid extension and as a means of poverty alleviation in remote regions. Moreover, experience indicates that productive use of electricity is indispensable for rural electrification to enhance economic development. But how are these issues regarded in countries with very limited rural economic development? In this study, influential power sector actors in Tanzania and Mozambique were interviewed on their perceptions regarding rural electrification strategies, private sector involvement, productive use of electricity, off-grid electrification, and renewable energy technologies. Tanzania and Mozambique face some of the lowest rural electrification levels in the world, and are currently undertaking substantial efforts to improve their situation. Findings indicate: a low interest among the private sector to get involved in power production and distribution; an appreciation of productive use of electricity but also a tendency to separate electrification from a broader rural development context; and a stronger credence in renewable energy and off-grid electrification in Tanzania compared to Mozambique.

1. Introduction

Access to electricity has proven to deliver substantial social benefits in rural areas of developing countries – related to lighting (Davis 1998, Gustavsson 2007b), education (Ellegård et al. 2004, WB 2008, Daka and Ballet 2011), health (Spalding-Fecher 2005), leisure (Ellegård et al. 2004, WB 2008), and security (WB 2008) – but evidence for enhanced economic development from rural electrification (RE) is weak (Barnes and Binswanger 1986, Foley 1992, WB 2008). Hindsight assessments of RE strategies and projects have repeatedly concluded that productive use of electricity, which in turn often implies complementary services such as infrastructure and business assistance, is an indispensable component for RE to boost economic development (Ranganathan 1993, Holland et al. 2001, Peters et al. 2009). In this respect, productive use refers directly to income-generating activities such as agricultural production, refining of tradable goods, and commerce. By improving business profits, productive use may increase ability-to-pay and demand for electricity. Thus, improvement of RE viability may eventually lead to structural change in communities (Mulder and Tembe 2008). However, contrary to expectations, productive use of electricity in RE projects has been limited (Wamukonya and Davis 2001, Iliskog and Kjellström 2008, WB 2008, Peters et al. 2009).

RE is a massive and expensive undertaking for any country, and developing countries are therefore dependent on financial assistance from donors and financial institutions, such as the World Bank. During the 1980-90's, the World Bank strategy on RE lending shifted from public energy sector support towards the promotion of energy sector reforms, with increased focus on economic and financial efficiency and strong emphasis on private sector involvement (Weisser 2004, WB 2008). In short, emphasis on the economic aspects has increased at the cost of the social aspects (equity, public services, 'electricity for all'). The World Bank scheme has been persuasive and most developing countries have now undertaken, or are undertaking, corresponding energy sector reforms. Although there is no universal answer to the outcome of these reforms the policy has been widely criticised (Karekezi and Kimani 2002, Wamukonya 2003, Karekezi and Kimani 2004, Weisser 2004). In essence, the criticism is related to the low interest of the private sector to get involved in RE, due to weak rural markets, and the general failure of reforms to provide RE benefits also for the poor. This shortcoming in poverty reduction is correspondingly recognized in the impact evaluation report published by the World Bank (2008).

The lowest RE levels are found in Sub-Saharan Africa, where both electricity generation and coverage of electric grids are heavily underdeveloped. The World Bank evaluation report concludes that future investments in African electric power infrastructure and efficiency must be massive, and that off-grid solutions can be justified as complements to grid extension, in order to ensure the inclusion of remote areas. The report further suggests that renewable energy technologies (RET) should be more involved and that support for productive use should be included in the schemes for RE projects. The options of off-grid RE and the use of small-scale RETs are not new to the discussion (Murphy 2001, Brent and Kruger 2009, Kirubi et al. 2009), but may be controversial in economic and efficiency-related terms as they may incur higher costs per customer and lower reliance in comparison to main grid extension.

Many African countries face an enormous challenge in boosting RE from very low levels under the impediments of weak rural markets and a growing global energy crisis. However, the continent is heaped with energy sources and several countries show promising economic growth. A review by Brew-Hammond and Kemausuor (2009) concludes that "efforts which succeed in integrating productive uses and income generation activities into energy access initiatives, whether based on conventional fuels or renewable energy, may well turn out to be

the deciding factor if the dream of energy for all in sub-Saharan Africa is to become a reality in the foreseeable future" (s 83).

In this study, power sector actors in Tanzania and Mozambique were interviewed on their perspectives regarding productive use, private sector involvement, off-grid solutions, and prospects of renewable energy in the RE undertakings of their respective countries. Our aim is to explore how these – according to the literature – important matters for successful RE are perceived by policy makers and implementers of RE.

1.1. Productive use of electricity

Most industry and manufacturing workshops require, or at least benefit from, electric power. Likewise, agricultural output can be greatly improved with the use of electricity for e.g. irrigation, dehulling/milling, or lighting in dairy and poultry farms (Barnes and Binswanger 1986). In the absence of electricity, rural industries and well-off farms and workshops may use own diesel generators, although it is a comparatively expensive means of electricity. Furthermore, where grid-supplied power is unreliable, rural industries often continue to use their own generators even after electrification (WB 2008, VPC 2008). Industry and manufacturing need power of high quality and high capacity, the latter making low-power sources such as solar photovoltaic unsuitable for this purpose (Holland et al. 2001, Jacobson 2007). For example, the connection to the main electricity grid of a rural cotton factory improved agricultural output (Mulder and Tembe 2008) in a village in Mozambique, while the low quality of diesel generated power (and the reliance on expensive private generators) created a major energy bottleneck for industrial production in another village in the same country (VPC 2008). Reliability can be a problem also for grid-connected customers in urban areas, as blackouts and power rationing are common phenomena, incurring costs to connected industry and business due to temporary surcharges that damage equipment.

Although it has often been assumed that access to electricity will spur production and lead to industrial development, this has rarely been shown in practice. So far, this assumption has mostly been shown to be correct only at a home-business scale, where there is evidence of increased income, mainly due to lighting and extended working hours (WB 2008). These shortcomings on productive use in RE may be strongly related to the lack of complementary services (Pearce and Webb 1987, Ranganathan 1993, Holland et al. 2001). 'Complementary services', in this respect, is synonymous with co-development of different sectors and hence, is an issue of rural planning. Transport infrastructure is necessary to trade goods, adequate financial institutions must be available to producers at all levels, appliances should be locally available, and there must be an awareness of the electric power potential. As expressed by Kankam and Boon (2009) on the evaluation of RE projects in Ghana: "The absence of other rural infrastructure and markets that complement energy use for small and micro enterprises' growth and development tends to negatively impact job creation opportunities" (p 217).

In short, electric power has the potential to increase profits from local production and may be a prerequisite for – but not a seed of – economic development in rural areas. But integration with, or at least parallel development of, other services is necessary.

1.2. Off-grid and RET

Off-grid RE, that is rural electrification based on independent isolated systems exclusively meeting the local demands of remote locations, is a complement to national grid extension. In a long time perspective, off-grid may be regarded as a temporary solution because large interconnected grids with a multitude of supply sources have technical advantages related to power quality, and can utilize the generated energy more effectively (no excess power)

(Kaundinya et al. 2009). However, given the current pace of grid extension in countries like Tanzania and Mozambique, many areas are unlikely to have gain to the grid for another 50 years, so that off-grid systems are not necessarily temporary solutions but rather, the only available ones. So far, off-grid systems have primarily used diesel generators, which carry high costs as a consequence of fuel transport – and nowadays increased fuel prices. Further, diesel-based off-grid systems suffer from frequent power blackouts in many countries, due to insufficient maintenance (WB 2008, VPC 2008). An alternative to diesel is to use RETs for off-grid RE.

Geographically dispersed settlements and high abundance of renewable energy resources make RETs a particularly promising option for African RE, although there are challenges to overcome (Bugaje 2006, Brew-Hammond and Kemunoor 2009). Documented outcomes of off-grid systems based on RETs have been both encouraging and disappointing; successful African examples include micro-hydro programmes (Maher et al. 2003, Pigati and van der Plas 2009), and solar PV projects, which have at least resulted in social benefits (Ellegård et al. 2004, Bugaje 2006, Gustavsson 2007a, b). RET-based off-grid systems are often seen as more expensive than grid connections (Brent and Rogers 2010), but may still be justified from a poverty reduction perspective – so that remote areas are not left behind in the RE process. Moreover, technical development is making RETs increasingly competitive (WB 2008) and where water streams are available pico-hydro systems can be very inexpensive (Maher et al. 2003). In this context, comparison between technologies depends much on what is measured and for whom – for large or small-scale systems, for the investor or the consumer, in terms of cost per connection or cost per kWh?

1.3. Power sector and RE in Tanzania and Mozambique

Precise numbers of RE levels are difficult to derive and depend on which definition of 'rural' is used in each assessment – which rarely is clearly stated. The World Bank (2008) presented RE levels of 1.6% and 1.1% for Tanzania and Mozambique, respectively (data from 2003-2004). A Tanzanian household budget survey from 2007 estimated the RE level to be of 2-3% (REA 2011). With RE levels in this order of magnitude, and the great majority of the population living in rural areas, both countries are among the least electrified in the world and face enormous RE challenges. Both countries introduced energy sector reforms during the 1990's and 2000's, including commercialization and market liberalization.

The Tanzanian power sector

The Tanzanian power generation is based on hydropower and natural gas (run by the private company Songas), with some contributions from agro-industry co-generation. The off-grid systems are based mostly on diesel generators, although a few RET-based systems have been installed (in addition to a growing number of private solar home systems). Before the energy sector reforms, the public utility Tanesco (Tanzania Electric Supply Company) was responsible for RE. As part of the reform, the power market was liberalized and measures were taken to attract private sector involvement. The responsibility for RE then shifted to the governmental Rural Energy Agency (REA, operational in 2007), operating under the Ministry of Energy and Minerals (MEM). REA aims to facilitate RE through financial support (up to 30%) of RE projects, to enhance private sector involvement, and increase the use of RETs. This far, however, interest from the private sector has been limited and most funding has entered Tanesco-driven RE projects.

Tanesco carries out RE by following a master plan which prioritizes electrification of district capitals. Both grid extension and off-grid projects are undertaken, although the former

2. Methods

On two separate occasions in 2010 and 2011, two researchers carried out interviews with energy sector actors in Tanzania and Mozambique. In addition to the interviews, some of the electrification projects that had been referred to by the actors were visited in the field for personal observations.

The Mozambican power sector

alternative is favoured. Along the transmission lines, villages meeting economic development-oriented criteria are electrified. Tanesco tariffs are negotiated through the Energy and Water Utilities Regulatory Authority (EwURA), which also negotiates the price of electricity sold by small private producers to the Tanesco grid, and the feed-in tariff for Tanesco's own generation costs and is consequently much higher (about a factor of three) for electricity sold to off-grid systems in comparison to electricity sold to the main grid (EwURA 2011b, a). This feed-in tariff recently became operational and is a means to attract private producers in rural areas. In addition to Tanesco, off-grid RE in Tanzania is carried out by NGOs, church communities, and project-funding donors (all of which can access the feed-in tariff in case they sell to Tanesco). The financial contribution from donors to the energy sector is fundamental and international consultancies play an important role in planning, both at the strategic and the project level.

Most of Mozambique's electricity infrastructure was destroyed during the civil war, which ended in 1992. Since then, the public power utility EdM (Elevtricidade de Moçambique) has undertaken massive grid extensions. The main power source in Mozambique is the Cahora Bassa hydropower dam situated in the far North-West part of the country. The almost 2 GW capacity of Cahora Bassa far exceeds domestic consumption, thus, most power is exported. There are few other power stations in Mozambique, although there are plans for expansion of hydropower. In addition, substantial coal reserves have been found in the same geographical area as Cahora Bassa (Tete province).

Although the market was liberalized by the energy sector reforms, private sector is virtually absent in the power sector, particularly so in RE. EdM focuses on grid-extension and has almost reached the current master plan priority of electrifying all district capitals (some of which are supplied by off-grid systems). The governmental foundation Funae (Fundo de Energia, initiated in 1997), operating under the Ministry of Energy, has the objective of improving access to energy in rural and urban areas, including the promotion of private sector involvement and increased use of RETs (FUNAE 2007). In practice, Funae is responsible for off-grid electrification which is mainly carried out by supplying solar PV systems and diesel generators to remote areas, following directions from central and regional authorities.

Mozambique has few NGO's involved in the power sector but, just like in Tanzania, donors and international consultancies play important roles.

Table 1. Interviewed actors and their role in respective organisation.

	Actor	Description of organisation/division	Role in organisation	Category
Tanzania	MEM	Ministry	Commissioner	Policy-maker
	TanESCO-A	Power utility: distribution	Management	Policy-maker
	TanESCO-B	Power utility: distribution	Directorate	Policy-maker
	TanESCO-C	Power utility: research	Research	Policy-maker
	REA	Rural energy agency	Directorate	Policy-maker
	EWURA	Regulatory authority	Management	Policy-maker
	NGO	Energy related development	Management	Implementer
	Donor	Energy sector support	Program officer	Policy-maker
	Consultancy-A	Consultancy	Management	Implementer
Mozambique	EdM-A	Power utility: generation	Directorate	Implementer
	EdM-B	Power utility: rural province	Directorate	Implementer
	EdM-C	Power utility: remote rural province	Directorate	Implementer
	EdM-D	Power utility: distribution	Directorate	Policy-maker
	Funaec	Rural energy agency	Management	Implementer
	Consultancy-B	Consultancy	Management	Implementer
	Consultancy-C	Consultancy	Management	Implementer

2.1. Interview methodology and topics

The interviews were semi-structured and open-ended. The respondents (actors) were asked questions that were pre-determined by topic and content but not by precise phrasing, with the option of follow-up questions on relevant matters (Mikkelsen 2005). The questions regarded six topics: RE strategies; the importance of different (non-specified) energy loads for successful outcome of RE; the importance of productive electricity uses; the involvement of

the private sector in the RE market; the importance of off-grid solutions for RE; and opinions on utilizing RETs. RETs covered in this study include various solar PV applications, small and micro-scale hydro plants, wind turbines, and biomass co-generation in industry. The focus is primarily on electricity, leaving out biogas, biodiesel, and improved stoves. Bioenergy technologies for cooking and transport may be equally important, but outside the scope of this study. Geothermal energy was referred to in several interviews and is therefore presented in the results, although it is not typically linked to RE.

In the case interview topics were not familiar to, or within the responsibility of, the interviewed actor, the discussion moved on to the next topic. Most interviews took 50-70 min and were held in English, with the assistance of Portuguese-speaking interpreters when needed.

Interviews were recorded (unless circumstances did not allow), transcribed, and analysed through content analysis methodology (Mikkelsen 2005). The content analysis provides an iterative process, where content categories are based on pre-defined themes of interest (deductive analysis) and sub-categories may emerge from the material (inductive analysis).

2.2. Actors

Interviewed actors were selected on the basis of their professional position, with the aim of interviewing representatives from the most important organisations in RE policy-making and implementing (authorities, agencies, utilities, consultancies, donors, non-governmental organisations (NGO)). The authors were assisted by colleagues from the University of Dar es Salaam and the Universidade Eduardo Mondlane in the identification of adequate actors to be part of the study.

Sixteen actors within eleven organisations were interviewed (Table 1). Number of actors exceeds the number of organisations because separate divisions and provincial head offices within large power utilities were considered different actors. Moreover, some actors were represented by more than one respondent during the interview. To avoid personal exposure, the full details of interviewees are undisclosed. As a brief indicator of responsibility, the actors were categorized either as policy-makers (involved in central planning) or implementers (involved in field surveying or detailed planning of implementation). For some actors, the borders between these categories are vague. For example, consultants are employed both to perform detailed planning in field and to develop strategic planning documents.

The Tanzanian organisations and actors are: Ministry of Energy (MEM); TanESCO power utility (TanESCO-A, TanESCO-B, and TanESCO-C); the Tanzanian Rural Energy Agency (REA); the Energy and Water Utilities Regulatory Authority (EWURA); a foreign donor agency (Donor); a local non-governmental agency involved in rural energy (NGO); a foreign power sector consultancy (Consultancy-A).

The Mozambican actors were: Electricidade de Moçambique (EdM-A, EdM-B, EdM-C, and EdM-D); the Mozambican rural energy agency (Funaec); two foreign power sector consultancies (Consultancy-B and Consultancy-C).

3. Analysis of results

Table 2. Depiction of typical aspects in operative RE strategies, categorized into growth-related and social aspects, and actors' note on the 'most important loads' for successful outcomes of RE projects, categorized as PU (productive use, i.e. industries, mills, irrigation, manufacturing workshops, fish markets, business, tourism), PS (public services, i.e. health centres, schools, public lighting, water pumping), HH (households), and AD (administrative buildings).

Actor	RE strategy				
	Growth aspects	Social aspects	PU	PS	HH AD

Tanzania	MEM	•	•	•	•
	TanESCO-A	•	•	•	•
	TanESCO-B	•	•	•	•
	TanESCO-C	•	•	•	•
	RBA	•	•	•	•
	EWURA	•	•	•	•
Mozambique	NGO	•	•	•	•
	Donor	•	•	•	•
	Consultancy-A	•	•	•	•
	EDM-A	•	•	•	•
	EDM-B	•	•	•	•
	EDM-C	•	•	•	•
	EDM-D	•	•	•	•
	Funae	•	•	•	•
	Consultancy-B	•	•	•	•
	Consultancy-C	•	•	•	•

3.1. The role of productive electricity use in RE

In both countries, the power distribution master plan directs rural electrification, towards district capitals, and emphasizes productive electricity use as important criteria. In this context, productive uses of electricity range from small enterprises or use of machinery (mills, workshops, chicken farms, agricultural irrigation) to rural industry (e.g. cashew nut factory, saw mill). In Tanzania, all actors who shared their reflections on prevalent RE strategies, mentioned economic aspects (Table 2). However, social aspects – equity-based – were only emphasized by MEM, RBA, and EWURA – all of which are involved in policy-making rather than in field implementation. In Mozambique, social aspects of RE were accentuated by most actors, in addition to economic aspects. It can be noted that the two actors EDM-C and Funae, responsible for remote-province electrification and remote area off-grid RE, respectively, only mentioned social aspects. The difference between central and remote provinces may be exemplified by EDM-A, operating from the Mozambican capital Maputo:

"What we electricity is, for example, a cashew factory or some cotton processing factories ... we visit a district and see the potential, then we prioritize."

Conversely, operating from a remote province of the same country, EDM-C stated that:

"Large consumers are not the main purpose, the village is the priority ... the motivation is to increase quality of life for rural people."

Actors' reflections (Table 2) indicate that economic aspects are recognised by most actors in both countries, but also that the social aspects appear to be more uttered in Mozambique. Literature suggests that economic development may only be boosted if electricity is used for productive activities (section 2). Accordingly, in Tanzania, all actors mentioned productive uses as the 'most important loads' for successful RE (Table 2), while other loads were only mentioned by two actors (TanESCO-C and RBA). This should not be interpreted as other loads are not considered important; after all, most RE campaigns strive to connect communities not entities; but doubtless, productive use loads were considered the most important for success in this country. As framed by RBA:

"First and foremost the load for productive use [is important], since we know that productive use is the most important component that can provide the standard of living for the rural people. The livelihood of rural people cannot be increased by only using electricity for lighting ... So, first and foremost, for productive use, and secondly also for households."

The perceptions of most important loads were more diverse in Mozambique. Most actors mentioned productive uses, but public services and administrative buildings were given more attention than in Tanzania. The only actor who did not mention productive use as most important for RE project success was Mozambican EDM-C, who is responsible for electrification in one of the most remote provinces of the countries. This may imply that less emphasis is given to small-scale productive uses in the allocation of RE resources. For example, EDM-B explained:

"The purpose is to connect [households], but EdM also need to sell electricity so we look for industries, mills and production. But the main purpose is the people and not to find industries"

Further, EdM-C explained:

"We are looking for the big companies so they can [financially] attract EdM to come with the line, but small industry is not enough"

Despite the ambition to identify and connect rural industries to electrification projects, the industries were, by all actors, perceived to be very few, or virtually absent. Small-scale agro-processing and manufacturing workshops were considered more common. In this rural context, where most people are without access to electricity, even grain mills (often run by groups of women) and small businesses are considered important and may have a large impact on the local economy. However, grid extension and transmission sub-stations are expensive and small-scale production cannot motivate grid connection from the utility's financial perspective (Mulder and Tembe 2008).

The feeling of being set-aside despite having an electricity-dependent business was illustrated by a Mozambican poultry farmer who was visited in the area of EdM-C's responsibility. The farmer had his property a few hundred meters from the distribution line but reported that he was denied connection, unless he covered the full cost himself. In its place, the farmer continued to run his business on producer gas.

In contrast to the above-cited EdM actors, Funae underscored the importance of small-scale productive use in RE. Funae runs projects not only with diesel generators, but also with solar PV systems with low capacity factors, i.e. which do not match productive use loads:

"What needs to be known is that, what is very important to us is productive use, and solar PV has a big limitation; that is the big problem."

Most actors had the perception that access to electricity is a catalyst to development – if electricity is provided, development will improve. Tanzanian MEM explained:

"I believe that there are many entrepreneurs in the rural areas, but they cannot do anything without power. They cannot have milling machines, only a few can afford diesel generators. You cannot have lumber workshops and such things if you don't have electricity. So, I want to look beyond what is on the ground when I provide power ... for a long time we have looked at electricity as a luxury, but no, it is a necessity for development."

Mozambican EdM-A recalled a conversation with the African Development Bank:

"They said 'no we cannot bring electricity to this place, there is no demand'. I said, 'no, the demand is already there, if you bring electricity then you will see what will happen, they will buy lamps, fridges, they will improve.'"

Most actors perceived productive use as important, but what was most enthusiastically depicted was the 'large potential for agricultural production' in not-yet electrified areas, to be boosted into growth once electricity is provided. However, this requires new market structures

and strategies. During the visits at various projects in both countries, it became clear that there is a general lack of markets for agricultural products. For example, in the South Western highlands of Tanzania, most farmers grow the same crops creating marketing problems for consumer products such as bananas, which seasonally flood the local market, lowering prices both locally and for export to other regions. The Mozambican actors EdM-A and Funae mentioned the importance of complementary services in arguing that provision of electric appliances or micro-finance institutions are important supplements to RE – although it is only occasionally provided in practice. The Tanzanian Consultancy-A argued that the lack of complementary services and cross-sectorial planning is a major impediment to economic development. All three actors who raised the issue of complementary services are implementers of RE, with long experience of working in field. When policy-making actors were asked about complementary services as a follow-up question Tanzanian MEM established that there is little coordination between endeavours of different sectors:

"No, everyone is running on his own; it is a good idea but at the moment there is no coordination."

The regulatory authority EWURA confirmed that there is currently a lack of coordination between Ministries and rural development actors, but noted that there had been discussions with REA regarding extending the agency's responsibility from RE to a more comprehensive rural planning. Reference was made to Zimbabwe, where financial assistance for small-scale investments is offered to new rural electricity consumers. In Mozambique, EdM-D referred to the coordination of rural development projects controlled by the governmental cabinet CRE. All external funding receiving Mozambique has to pass through CRE, which directs the resources and strive to coordinate projects on infrastructure, agriculture, water, health, communication, and electrification. This indicates that there are coordination at higher level although this was not mentioned by many of the actors.

According to the Tanzanian NGO, there is no organizational or institutional structure in place at the district level for energy issues, i.e. there is no government office for energy, or person responsible for energy, which local actors can talk to. The NGO works to integrate energy with other development issues in order to engage local politicians and officials in energy projects.

3.2. Private sector involvement in power sector and RE

The energy sector reforms enabled the private sector to get involved at all levels of the power market, but repeated criticism among scholars has warned of low interest for the private sector to take any responsibility in RE (Wamukonya 2003, Karekezi and Kimani 2004, Haanyika 2008). Regarding private sector involvement the interview results (Table 3) show differences between the two countries.

In Tanzania, several actors experienced that private sector is encouraged to get involved in generation and RE, but in practice this is still not taking place. MEM, Tanesco-A, and REA all stated that there is a large potential for private sector contribution. In addition to the large natural gas company Songas, which is an important supplier at the national level, co-generating agro-industries were the common examples of private sector actors. Small private producers and churches running micro-hydro generators and distributing in own grids were also mentioned. None, however, perceived the private sector to hitherto have played an important role. EWURA noted that the financial institutions' low interest for the energy sector inhibits particularly small private investors:

Table 3. Content of actors' reflections on private sector (P) involvement in generation and RE, and given examples.

Actor	Private sector (P) involvement	Examples of involved P
Tanzania		
MEM	PS is encouraged; PS has large potential; PS involvement is low	Songas and a few co-generating industries and small private producers
TanESCO-A	PS is involved; PS has large potential	Co-generating industries sell to main grid, or by using own grids
TanESCO-B	PS is involved	Songas and co-generating industries sell to main grid
TanESCO-C	PS is encouraged; co-generation is a research focus area	Co-generating industries sell to main grid, small private producers sell to neighbours
REA	PS is encouraged; PS has large potential	Co-generating industries sell to main grid, the church provides some distribution
EWURA	PS is encouraged; PS involvement is low; PS interest is low	Songas and a few small private producers
NGO	PS is encouraged; PS involvement is low	A few private producers and churches
Donor	PS is encouraged; PS involvement is low	PS interest is low; competition with the gas industry is not encouraged
Consultancy-A	PS involvement is low; there is no incentive for PS	A few co-generating industries sell to neighbouring villages
EDM-A	PS involvement is low	A gas company and a coal mine sell electricity, but not in our province
EDM-B	PS involvement is low	
EDM-C	PS involvement is low	
EDM-D	PS involvement is low	
Funae	PS involvement is low; there is no incentive for PS	
Consultancy-B	PS involvement is low; there is no incentive for PS	Few co-generating industries; gas and railway companies have not succeeded
Consultancy-C	PS involvement is low; there is no incentive for PS	Co-generating industries sell during excess periods

12

In response to this problem, MEM reported to have allocated credits of 23 million USD to facilitate loans to small private producers, in collaboration with the World Bank. Consultancy-A mentioned several barriers to private sector involvement, including unreliable RE markets (distribution), low entrepreneurship experience among local actors, and unreliable tariffs due to political involvement. Consultancy-A:

"The only interest private investors may have is generation, not distribution. There is no one who can run distribution, it has been tried out [but it failed], it is impossible. And no one is interested in rural electrification on private basis, it can never be viable."

The Donor acknowledged the necessity of subsidizing not only user fees and government-led RE, but also private RE incentives, while Consultancy-A argued that the donors' policies do not allow for support from the private sector, thus hindering its involvement.

Among the Mozambican actors, all actors perceived the involvement of the private sector to be low. The low interest for private involvement in the power sector was associated with the very low tariffs resulting from inexpensive hydropower generation, referred to as the 'Cahora Bassa-effect'. The inexpensive hydropower inhibits the opportunities for private sector. Mozambican actors explained that experience has shown how higher tariffs used in private off-grid systems are difficult to be accepted by customers, because the price difference compared to main grid tariffs becomes too large. Moreover, there is constant insecurity of getting prices dumped, should the main grid be extended to the area. Consequently, the private sector has little interest in either grid-connected power generation or off-grid RE. As explained by two EDM actors:

"The electricity price from EDM is too low for competition," "You will spend all your money."

However, it is not only competition with inexpensive hydropower that hinders private sector involvement in Mozambique; electric grid infrastructure is expensive and the rural ability-to-pay is low. Consultancy-C explained:

"Only the capital, and possibly some other bigger cities, may be of interest [for private sector involvement]. The energy sector reform came 50 years too early, commercialisation is unwise since it is so expensive to build infrastructure."

In summary, even though Tanzania has encouraged private sector involvement and the expectations on the private sector are higher among interviewed actors in this country, it was fully agreed among interviewed actors in both countries that private sector is not very involved in electrification, and even less so in distribution and RE. It should be noted, though, that the reforms are still taking place and some incentives, such as the Tanzanian feed-in tariff for small producers in off-grid systems, are very recent (under implementation at the time of the first interviews).

13

Table 3. Actors' reflections on the potential and applicability of different renewable energy technologies. Content sorted from positive to negative where H is small/micro hydropower, S is solar PV, W is wind power, G is geothermal energy.

	Actor	Positive			Neutral		Negative		
		Passionate	High potential	Of interest	Not much considered	Restricted usefulness	Too expensive	Too high variations	Too low potential
Tanzania	MEM	H S W		G		S			
	TanESCO-A						W	W	
	TanESCO-B		H	W					
	TanESCO-C		H	W G					
	REA		H S	W G					
	EWURA		H	S	W		S		
	NGO		S	H		S			
	Donor		H	S					
	Consultancy-A	H	G			S	S		W
	EdM-A	H S					S W	W	
Mozambique	EdM-B				H				W
	EdM-C	H							
	EdM-D						S W	W	
	Funae	H	S		W	S			
	Consultancy-B		H						
	Consultancy-C	H							

3.3. Off-grid electrification and renewable energy

Main grid extension is often the most cost-effective way of increasing electrification levels, particularly so when no long-distance transmission is required. Off-grid, however, may be the most cost-effective way of electrifying specific, remote/or small, communities. In order to enhance poverty-reduction impacts of RE, off-grid has gained increased attention both from donors and from the World Bank (2007).

Off-grid RE was recognised by several Tanzanian actors (Table 3), and its importance was particularly emphasized by MEM, REA, and the NGO. The former two actors have the responsibility to promote off-grid and the latter is involved in the implementation of off-grid RE. The TanESCO actors simply regarded off-grid as a part of RE without giving it much reflection, while Donor and Consultancy-A associated off-grid RE with complications related to ability-to-pay and organizational capacity.

Also in Mozambique the consultancies regarded off-grid electrification as a rather peripheral part of RE, but Consultancy-B pointed to the advantages of letting rural people get used to electricity before arrival of the main grid. EdM-B and EdM-C, who are responsible for electrification in far-north provinces of Mozambique, regarded off-grid RE important for reaching out to rural communities. But they both declared that the issue is the responsibility of Funae, aside situations when EdM has to take over off-grid generators that have failed due to lack of diesel and maintenance. EdM-D, with an overarching responsibility for RE in Mozambique, clearly stated that off-grid is the wrong way of allocating resources. EdM-D showed little interest in remote area electrification on the whole, and argued that few people live under conditions where off-grid can be justified. However, EdM-A was more enthusiastic about the potential for off-grid solutions:

"There is one thing that has fascinated me: off-grid electrification ... You can do it with mini- and micro-hydro, I think this is the future for Mozambique, we have a lot of rivers."

The opinion that off-grid should – or even must – be based on RETs was repeated by several actors in both countries. When deductively analysing the actors' reflections on diesel, it was found that none had referred to diesel generators in positive terms (although it was often understood as necessary). Most actors brought up diesel generators as a major problem in RE, due to high costs and difficulties of maintenance (Table 3). EdM-A explained how generation costs in diesel-based off-grid reach US\$ 33-44 per kWh, which is far too expensive for any economic viability. EdM-D simply declared:

"I don't want to listen to diesel more in my life."

RET-based off-grid was clearly preferred among actors, but the trust in RETs other than mini/micro-hydro was doubtful. Almost all actors regarded hydropower as being of high potential (Table 4). Also solar PV was generally perceived as valuable, but some actors also associated solar PV with particularly high costs and restricted usefulness (related to productive use, which requires a higher capacity factor than what is usually provided by solar PV systems). Wind power was regarded with scepticism in Mozambique while more positively so in Tanzania. On the whole, the Tanzanian actors appeared open-minded to a larger variety of RETs compared to the Mozambicans.

Geothermal energy is not relevant for small off-grid systems, but may be favourable for grid supply because of its consistency. In Tanzania, the potential of geothermal energy was recognised by MEM, TanESCO-C, REA, and Consultancy-A. The latter argued that, although

resource assessments have indicated good potential for this source, which is highly advantageous from an energy system perspective, geothermal energy has been neglected and discouraged due to political interests in the natural gas industry.

4. Discussion

4.1 Findings of the study

Even though the overarching RE strategy is similar in both countries, the importance of productive use and ability-to-pay were more strongly emphasized among actors in Tanzania, compared to Mozambique. In both countries the actors reported a high potential for increased agricultural production and manufacturing, but also depicted a poor rural market with very few industries. The results did not support the idea suggested by Mulder and Tembe (2008), that 'anchor-projects' – where electrified rural industries warrant a high power consumption, increase production and create jobs and economic development – are genetically available options for RE in the investigated countries. Instead, it is the small-scale rural production that has to be accounted for. Small-scale productive activities were generally considered important among the actors, particularly in Tanzania, which is in accordance with the literature (Barnes and Branswanger 1986, Holland et al. 2001, Brew-Hammond and Kemausuor 2009). However, the apparent lack of complementary services and coordination between different segments of rural development, may be an important barrier for RE to actually boost production, as was previously indicated by Kankam and Boon (2009) in Ghana. Particularly Tanzania was reported to suffer from lack of coordination and RE strategies would probably benefit from a broader rural development perspective, including micro-finance institutions and infrastructure.

In Tanzania, the main responsibility for promoting RE has been moved from the public utility Tanesco to the agency REA. REA does not carry out RE projects itself but strives to attract other actors to engage, mainly through financial support. In the absence of private investors, most support has gone to Tanesco. Previous research indicates that there is sufficient local capability for independent power producers and distributors to develop in Tanzania, and that the conditions of local financial institutions were the major constraining factors (Marandu 2002). With the improved conditions provided by REA (project funding) and EWURA (feed-in tariffs), these operators could be expected to proliferate. However, the rural energy market, because of low expected profits and limited experience of power sector businesses. Based on this result, there is an apparent risk of relying too much on private sector investments at this early stage of RE, as was predicted by Wamukonya (2003). A similar dilemma was shown by Haanyika (2008) in Zambia, where liberalization and efforts to attract private sector involvement in RE rendered little results and left the public utility to do the work, just as before the reform. Possibly, it would be more effective to encourage the private sector to invest in the use of electricity in rural areas, than to strive for its direct involvement in rural power generation and distribution.

In Mozambique, the private sector is virtually absent from the power sector, as a consequence of the 'Cahora Bassa effect' of very inexpensive large-scale hydropower. In Tanzania, however, the gas-industry and co-generating agro-industry provides some generation. The potential of increasing the contributions from co-generation has previously been remarked by Barnes (2007). It may be a valuable opportunity for both countries.

As rural populations are scattered, off-grid RE is the sole option to electricity access for many small remote communities. Indeed, sub-stations are expensive and even settlements in the vicinity of transmission lines can be left without electricity. Off-grid RE is a recognized part of remote area electrification in both countries that has been used in order to fulfil the strategy of electrifying district capitals. Diesel-based off-grid systems in remote areas were clearly regarded as highly problematic among most actors, but also guilt-by-association of off-grid with diesel generators have led to some scepticism towards alternatives to main grid extension. However, Funae and REA are now promoting alternatives based on RETs.

The possibility of using RET-based off-grid was enthusiastically supported by several actors, although some, such as EdM-D, were sceptical. By far, small/micro-scale hydropower was the most well-renowned RET. Moreover, experiences from neighbouring Kenya have shown that small (5 kW) hydropower systems can be truly inexpensive (Maher et al. 2003). Yet, almost none of the many small rivers and streams in northern Mozambique have been utilized. In Tanzania, micro-scale hydro is sporadically used by several of the interviewed actors. Interestingly, these church initiatives were referred to by some church communes. Even though none of these systems are not fully independent (they receive support from donors), the enthusiasm among RE actors indicates that such off-grid initiatives are very welcomed.

Many actors regarded solar PV as of high potential, but its limitations in respect to productive use were also remarked. Policy-making actors in Tanzania expressed great expectations on RET-based off-grid systems as means to combat the low RE levels. The Tanzanian economic incentives for RET systems are three times as high as for electricity sold to Tanesco's off-grid systems are three times as high as for electricity sold to the main grid (EWURA 2011b, a). As this feed-in incentive is new, evaluation will have to wait. Altogether, our results indicate a true encouragement of RET-based off-grid systems in Tanzania. On the contrary, in Mozambique there is a strong focus on main grid extension, and a somewhat higher scepticism towards off-grid and RETs, which is likely related to the 'Cahora Bassa effect'. Nonetheless, there is some support for off-grid RE also among the Mozambican actors, and the undertakings of Funae are growing.

4.2 Methodological weaknesses

Only one interview was held with each of the actors, this implies that the given answers reflect what the actors found important at that specific point in time, influenced by the interview situation.

Another potentially significant weakness of the study is the language. Even though interpreters were used on actors' demand, both questions and answers may be simplified or misunderstood when neither part speaks the mother language. The problem has been dealt with through triangulation of findings during the analysis.

This study includes the perspectives of some of the most influential actors in policy-making and implementation of RE, however, the top-level – the politicians – was not involved.

5. Conclusions

This paper has contributed to the understanding of how the policy-making and implementing actors involved in rural electrification in two of the most challenged countries in world perceive their situation and alternatives for progress. Productive use is understood as highly important, but is not straightforwardly encouraged due to the poor rural markets and limited coordination between electrification strategies and other rural development. Private sector is stimulated in Tanzania, and less so in Mozambique, but is in both countries perceived as difficult to get involved. It is suggested by the authors that more attention should be on involving private sector in supplying the means for rural production associated with use of electricity. Furthermore, it is shown that almost all actors have a negative experience of diesel generators – which in some cases contribute to a generally negative opinion on off-grid electrification in general. However, some actors are enthusiastic about the opportunities of using more renewable energy in off-grid systems. Among the renewable energy technologies hydropower is the preferred; as it is often available and can be used for productive use.

References

- Barnes, D. F. 2007. *The Challenge of Rural Electrification*. Resources for the Future Press (RFF Press), Washington.
- Barnes, D. F. and H. P. Binswanger. 1986. Impact of Rural Electrification and Infrastructure on Agricultural Changes, 1966-1980. *Economic and Political Weekly* 21:26-34.
- Block, E. 2007. Tidal power: an update. *Renewable Energy Focus* 9:58-61.
- Brent, A. C. and W. J. L. Kruger. 2009. Systems analyses and the sustainable transfer of renewable energy technologies: A focus on remote areas of Africa. *Renewable Energy* 34:1774-1781.
- Brent, A. C. and D. E. Rogers. 2010. Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context. *Renewable Energy* 35:257-265.
- Brew-Hammond, A. and F. Kemausuor. 2009. Energy for all in Africa -- to be or not to be?! *Current Opinion in Environmental Sustainability* 1:83-88.
- Bugaje, I. M. 2006. Renewable energy for sustainable development in Africa: a review. *Renewable and Sustainable Energy Reviews* 10:603-612.
- Daka, K. R. and J. Ballet. 2011. Children's education and home electrification: A case study in northwestern Madagascar. *Energy Policy* 39:2866-2874.
- Davis, M. 1998. Rural household energy consumption : The effects of access to electricity--evidence from South Africa. *Energy Policy* 26:207-217.
- Ellegård, A., A. Arvidson, M. Nordström, O. S. Kahumiana, and C. Mwanza. 2004. Rural people pay for solar: experiences from the Zambia PV-ESCO project. *Renewable Energy* 29:1251-1263.
- EWURA. 2011a. Appendix 2A Detailed tariff calculations for year 2011 for the sale of electricity to the main grid in Tanzania under standardized small power purchase agreements in Tanzania. Energy and Water Regulatory Authority, Dar es Salaam.
- EWURA. 2011b. Appendix 2B Detailed tariff calculations for year 2011 for the sale of electricity to the mini-grids in Tanzania under standardized small power purchase agreements in Tanzania. Energy and Water Regulatory Authority, Dar es Salaam.
- Foley, G. 1992. Rural electrification in the developing world. *Energy Policy* 20:145-152.
- FUNAE. 2007. Strategic Plan Summary (2008-2010). Fundo de Energia, Maputo.
- Gustavsson, M. 2007a. Educational benefits from solar technology--Access to solar electric services and changes in children's study routines, experiences from eastern province Zambia. *Energy Policy* 35:1292-1299.
- Gustavsson, M. 2007b. With time comes increased loads--An analysis of solar home system use in Lundazi, Zambia. *Renewable Energy* 32:796-813.
- Haanyika, C. M. 2008. Rural electrification in Zambia: A policy and institutional analysis. *Energy Policy* 36:1044-1058.
- Holland, R., L. Perera, T. Sanchez, and R. Wilkinson. 2001. Decentralised rural electrification : Critical success factors and experiences of an NGO. *Refocus* 2:28-31.
- Iliskog, E. and B. Kjellström. 2008. And then they lived sustainably ever after?--Assessment of rural electrification cases by means of indicators. *Energy Policy* 36:2674-2684.
- Jacobson, A. 2007. Connective Power: Solar Electrification and Social Change in Kenya. *World Development* 35:144-162.
- Kankam, S. and E. K. Boon. 2009. Energy delivery and utilization for rural development: Lessons from Northern Ghana. *Energy for Sustainable Development* 13:212-218.
- Karekezi, S. and J. Kimani. 2002. Status of power sector reform in Africa: impact on the poor. *Energy Policy* 30:923-945.
- Karekezi, S. and J. Kimani. 2004. Have power sector reforms increased access to electricity among the poor in East Africa? *Energy for Sustainable Development* 8:10-25.
- Kaundinya, D. P., P. Balachandra, and N. H. Ravindranath. 2009. Grid-connected versus stand-alone energy systems for decentralized power--A review of literature. *Renewable and Sustainable Energy Reviews* 13:2041-2050.
- Kirubi, C., A. Jacobson, D. M. Kammen, and A. Mills. 2009. Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya. *World Development* 37:1208-1221.
- Maher, P., N. P. A. Smith, and A. A. Williams. 2003. Assessment of pico hydro as an option for off-grid electrification in Kenya. *Renewable Energy* 28:1357-1369.
- Marandu, E. E. 2002. The prospects for local private investment in Tanzania's rural electrification. *Energy Policy* 30:977-985.
- Mikkelsen, B. 2005. *Methods for development work and research: A new guide for practitioners*. Sage Publications, London.
- Mulder, P. and J. Tembe. 2008. Rural electrification in an imperfect world: A case study from Mozambique. *Energy Policy* 36:2785-2794.
- Murphy, J. T. 2001. Making the energy transition in rural east Africa: Is leapfrogging an alternative? *Technological Forecasting and Social Change* 68:173-193.
- Pearce, D. and M. Webb. 1987. Rural electrification in developing countries : A reappraisal. *Energy Policy* 15:329-338.
- Peters, J., M. Harsdorff, and F. Ziegler. 2009. Rural electrification: Accelerating impacts with complementary services. *Energy for Sustainable Development* 13:38-42.
- Pigaht, M. and R. J. van der Plas. 2009. Innovative private micro-hydro power development in Rwanda. *Energy Policy* 37:4753-4760.

Ranganathan, V. 1993. Rural electrification revisited. *Energy Policy* 21:142-151.

REA. 2011. *Rural Energy Agency*.

Spalding-Fecher, R. 2005. Health benefits of electrification in developing countries: a quantitative assessment in South Africa. *Energy for Sustainable Development* 9:53-62.

Wamukonya, N. 2003. Power sector reform in developing countries: mismatched agendas. *Energy Policy* 31:1273-1289.

Wamukonya, N. and M. Davis. 2001. Socio-economic impacts of rural electrification in Namibia: comparisons between grid, solar and unelectrified households. *Energy for Sustainable Development* 5:5-13.

WB. 2008. *The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits*. World Bank Independent Evaluation Group, Washington DC.

Weisser, D. 2004. Power sector reform in small island developing states: what role for renewable energy technologies? *Renewable and Sustainable Energy Reviews* 8:101-127.

VPC. 2008. *Productive Uses of Energy*. Vattenfall Power Consultant, Maputo.

TE	Stressor source	Endpoints		Hazard and exposure pathway	EL	SR	TR
		Component	Indicator				
W:1 C:1 O:0	Maintenance works	Marine mammals	Abundance	Vessel movements cause disturbance and pollution; e.g. [23]	2	1	2
W:1 C:2 O:0	Transmission cables	Elasmobranchs	Foraging	Electric fields cause confusion in forage behaviour; e.g. [20]	2	1	2
W:3 C:2 O:0	Transmission cables	Fish, crustaceans, turtles, mammals	Abundance; Migration	Electromagnetic fields confuse, attract, or repel; e.g. [20]	2	2	2
W:2 C:2 O:0	Turbine	Marine mammals, fish, birds	Abundance	Underwater noise may cause stress or disturbed communication; e.g. [17]	2	1	2
W:2 C:1 O:0	Turbine	Marine mammals, fish	Migration	Underwater noise from turbine disturbs orientation; e.g. [20]	1	1	2
W:0 C:4 O:0	Turbine rotor	Environment / habitat	Hydrology & biogeochemistry	Absorption of kinetic energy affects local currents and sediment grain size; e.g. [26]	2	2	2
W:0 C:6 O:0	Turbine rotor	Fish; Waterfowl; Marine mammals	Abundance	Fast moving rotor blade causes collision; e.g. [27]	2	1	2
W:0 C:1 O:0	Turbine rotor	Marine mammals	Migration	Fast moving rotor blade causes avoidance and altered migration; e.g. [20]	1	2	2
W:0 C:0 O:4	Surface water intake	Plankton; Egg and larvae	Abundance; Recruitment	Entrainment and exposure to low temperatures increases mortality through cold shock; e.g. [28]	3	1	2
W:0 C:0 O:3	Water intake	Plankton, fish	Abundance; Recruitment	Impingement to intake filter causes injury or increased mortality to small organisms; e.g. [22]	2	2	2
W:1 C:2 O:0	Decommission	Marine mammals, fish, birds	Abundance	Extreme noise levels cause damage, stress or avoidance; e.g. [29]	2	2	1
W:1 C:1 O:0	Removal of device	Epibenthos; fish	Abundance	Removal of artificial structures reduces heterogeneity and habitats; e.g. [20]	2	1	1

Acronyms used in table:

TE Technology under assessment: W – Wave power, C – Tidal current power, O – Ocean thermal energy conversion. Digits indicate number of reviewed papers that propose the exposure pathway.

EL Evidence level of proposed exposure pathway: 1 – qualified suggestions, 2 – referring to effects of similar stressors / modelling works, 3 – providing own significant data.

SR Spatial range of effects: 1 – local, 2 – regional.

TR Temporal range of effects: 1 – momentary (during construction/decommission), 2 – persistent (during lifetime of device).

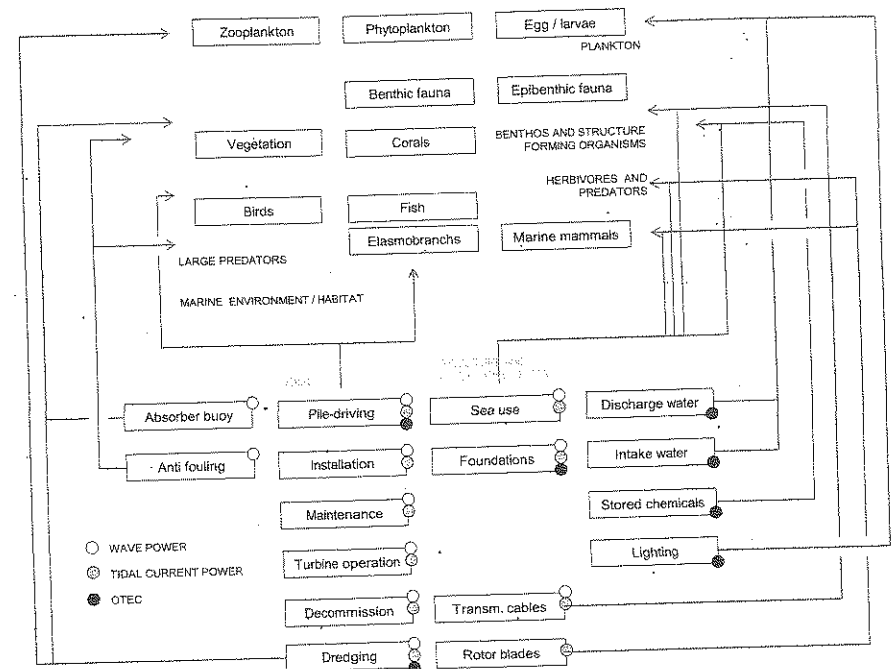


Fig. 2 Simplified conceptual model of exposure pathways between the technical system (stressor sources) and the ecological system (endpoints) according to the results of the literature search presented in Table 1.

It should be noted that most of the reviewed papers take a conservative approach when suggesting potential impacts, which means that there is a tendency to exaggerate rather than overlook risks. In some papers hazards and exposure pathways were suggested while at the same time the magnitude of impacts were thought to be of low importance (such as the effect of wave power devices on the hydrodynamic conditions [30] [31]). Further, some impacts – such as the reef-effect – may be considered positive from an environmentalist perspective, even though they imply a change to the pre-existing state of the ecosystem.

Subsequently, the results are used to discuss the applicability of EcoRA for future ecosystem-based assessments.

V. ECOLOGICAL RISK ASSESSMENTS OF OCEAN ENERGY

As shown by our results the number of potential endpoints is high. In risk assessments applied at the ecosystem level there is an obvious danger of “having to assess everything”.

TABLE 2
RISK-RANKING SCORES FOR ENDPOINTS BASED ON THE ANALYSED MATERIAL

Endpoints	Wave power	Tidal power	OTEC
Marine mammals	40	40	10
Fish (incl. elasmobr.)	22	22	26
Birds	30	30	10
Environment/habitat	12	16	13
Algae (sessile)	12	6	14
Epibenthic fauna	14	8	6
Plankton	0	0	19
Eggs / larvae	2	2	12
Electrosensitive fauna	8	8	0
Benthic fauna	4	4	2
Corals	2	2	6

TE	Stressor	Endpoints	Hazard and exposure pathway	EL	SR	TR
----	----------	-----------	-----------------------------	----	----	----

TE	Stressor	Endpoints	Component	Indicator	Hazard and exposure pathway	EL	SR	TR
W1	Dredging	Benthos; Corals	Abundance	Dredging causes increased turbidity and potentially release of contaminants and oxygen consuming organic matter; e.g. [16]	2	1	1	C1
W3	Installation	Benthos; Eggs and Larvae	Abundance; Recruitment	Installation of structures and cable trench remove natural seabed and increase turbidity; e.g. [17]	2	1	1	C2
W1	Installation	Marine mammals; Fish	Abundance	Installation activities and vessel movements cause disturbance and pollution; [18]	2	2	1	C3
W1	Installation	Waterfowl	Migration	Installation activities and vessel movements	2	2	1	C1
W3	Pile driving	Marine mammals; fish, birds	Abundance	Underwater noise causing damage, stress or avoidance; e.g. [20]	2	2	1	C3
W1	Sea use	Fish	Abundance	Acquisition of space prohibits fishery; e.g. [18]	1	-	-	C1
W2	Absorber	Environment/habitat	Hydrology	Absorption of wave energy impose changes in physical conditions; e.g. [3]	2	1	2	C6
W2	Absorber	Epibenthos; Algae	Chemistry (Coloniza- tion	Artificial structures provide additional habitat; e.g. [21]	3	1	1	C6
W0	Accidental	Environment/habitat	Abundance	Emissions of working fluid cause toxic effects or e.g. [22]	1	1	1	C0
W2	Anti-fouling	Marine mammals; Environment/habitat	Abundance	Continuous release of biocides cause toxic effects; e.g. [23]	2	1	2	C2
W0	Discharge	Corals; Fish; Larvae	Abundance; Recruitment	Changes in water temperature increase mortality or inhibit reproduction; e.g. [3]	2	1	2	C0
W0	Discharge	Mid-water environment / habitat	Hydrology & biogeo- chemistry	Water containing chlorine, trace metals, nutrients and altered temperature changes conditions at discharge depth; e.g. [22]	2	1	2	C0
W0	Discharge	Primary producers; Environment / habitat	Primary production; & biogeo- chemistry	Artificial upwelling changes hydrological conditions in the coastal zone; e.g. [16]	2	2	2	C0
W4	Foundations	Algae; Epibenthos; Fish; Marine mammals; Birds	Abundance; Coloniza- tion	Artificial structures increase heterogeneity and provide additional habitat, causing reef-effect; e.g. [24]	3	1	2	C2
W4	Foundations	Environment / habitat	Hydrology & biogeo- chemistry	Artificial structure affects water movements and local physical conditions; e.g. [20]	2	1	2	C3
W3	Foundations	Marine mammals	Abundance; Migration	Artificial structure disturbs or poses risk for entanglement and functions as a barrier; e.g. [25]	2	2	2	C0
W1	Foundations	Waterfowl	Abundance; Migration	Artificial structure disturbs or poses risk for collision and functions as a barrier; e.g. [19]	2	2	2	C1
W0	Facility	Plankton; Fish	Abundance	Artificial light attracts or repels fauna; e.g. [16]	2	1	2	C0

impact" in combination with either "wave power", "tidal power", or "OTEC". For each of the three search combinations the first 100 articles, sorted per relevance, were browsed in order to select papers in which links (pathways) could be an example.

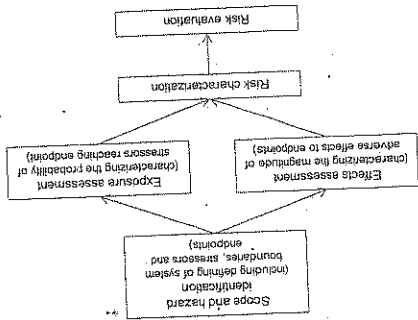


Fig. 1 Conceptual model of the procedure for EcoRA in the context of ocean energy. Modified from [10] and [11].

Risk assessment is a systematic way of estimating risk levels that emphasizes the handling of uncertainties to a higher extent than most other schools of environmental assessments. The specific ECORA methodology refers to risks from human actions to the natural environment [12]. The ECORA procedure is structured around three sources, exposure pathway and endpoints. The main steps of the procedure are [12] [13]: scope (including the definition of system boundaries and assessment endpoints), hazard assessment and interpretation. The applied risk-ranking method should be understood and interpreted as the simplest way of scoring.

IV. RESULTS

IV. RESULTS

The performed hazard identification, compiled in Table 1, reflects current perceptions on ecological risks from the three different ocean energy technologies. The suggested pathways are conceptually depicted in Fig. 2 and it is shown that many ecosystem components may come under exposure by the different ocean energy technologies. The risk-ranking, summarized in Table 2, indicates that wave power and tidal current power pose their highest risks to marine mammals, followed by birds and fish (including elasmobranchs). These hazards are associated with e.g. blocking of migration routes, reef-effect, collision, and electromagnetic fields. OTEC seems to pose highest risk to fish followed by plankton. Further, OTEC poses a much higher risk to eggs and larvae than other technologies. The major hazards from OTEC are associated with the risk of entrapment and impingement in in-take pipes for small fish and plankton (incl. eggs/larvae), and with the pre-existing habitats and hydrodynamic conditions, inducing changes in water temperature and nutrient level. Alteration of secondary effects on organisms, is an impact of high potency that has been suggested for all three technologies.

REFERENCES

- [1] B.D. Ferro, *Wave and tidal energy: Its Emergence and the Challenges it Faces*, *Refocus*, 7 (2006) 46-48.
- [2] J. Khan, G.S. Bhuyan, *Ocean Energy: Global Technology Development Status*, Powertech Labs, Surrey, 2009.
- [3] R. Pelc, R.M. Fujita, *Renewable energy from the ocean*, *Marine Policy*, 26 (2002) 471-479.
- [4] R. Costanza, F. Andrade, P. Antunes, M. van den Belt, D. Boersma, D.F. Boesch, F. Catarino, S. Hanna, K. Limburg, B. Low, M. Molitor, J.G. Pereira, S. Rayner, R. Santos, J. Wilson, M. Young, *Principles for Sustainable Governance of the Oceans*, *Science*, 281 (1998) 198-199.
- [5] B.S. Halpern, S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'Agrosa, J.P. Bruno, K.S. Casey, C. Ebert, H.E. Fox, R. Fujita, D. Heinemann, H.S. Lenihan, E.M.P. Madin, M.T. Perry, E.R. Selig, M. Spalding, R. Steneck, R. Watson, *A Global Map of Human Impact on Marine Ecosystems*, *Science*, 319 (2008) 948-952.
- [6] L. Crowder, E. Norse, *Essential ecological insights for marine ecosystem-based management and marine spatial planning*, *Marine Policy*, 32 (2008) 772-778.
- [7] F. Douvère, *The importance of marine spatial planning in advancing ecosystem-based sea use management*, *Marine Policy*, 32 (2008) 762-771.
- [8] C. Ehler, F. Douvère, *Marine Spatial Planning a step-by-step approach toward ecosystem-based management*, IOC Manual and Guides, Intergovernmental Oceanographic Commission, Paris, 2009.
- [9] G. Suter, L. Barnhouse, *Assessment Concepts*, in: G. Suter (Ed.) *Ecological Risk Assessment*, Lewis Publishers, Michigan, 1993.
- [10] G. Suter, *Predictive Risk Assessment of Chemicals*, in: G. Suter (Ed.) *Ecological Risk Assessment*, Lewis Publishers, Michigan, 1993.
- [11] J. Burger, C. Gordon, J. Lawrence, J. Newman, G. Forcey, L. Vlietstra, *Risk evaluation for federally listed (roseate tern, piping plover) or candidate (red knot) bird species in offshore waters: A first step for managing the potential impacts of wind facility development on the Atlantic Outer Continental Shelf*, *Renewable Energy*, 36 (2011) 338-351.
- [12] G. Suter, *Defining the Field*, in: G. Suter (Ed.) *Ecological Risk Assessment*, Lewis Publishers, Michigan, 1993.
- [13] M. Burgman, *Risks and Decisions for Conservation and Environmental Management*, Cambridge University Press, Cambridge, 2005.
- [14] I. Linkov, D. Loney, S. Cormier, F.K. Satterstrom, T. Bridges, *Weight-of-evidence evaluation in environmental assessment: Review of qualitative and quantitative approaches*, *Science of The Total Environment*, 407 (2009) 5199-5205.
- [15] (2011) SciVerse, ScienceDirect [online]. Available at: <http://www.sciencedirect.com/>
- [16] M.S. Quinby-Hunt, D. Sloan, P. Wilde, *Potential environmental impacts of closed-cycle ocean thermal energy conversion*, *Environmental Impact Assessment Review*, 7 (1987) 169-198.
- [17] O. Langhamer, *Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden)*, *Marine Environmental Research*, 69 (2010) 374-381.
- [18] Z. Defne, K.A. Haas, H.M. Fritz, *GIS based multi-criteria assessment of tidal stream power potential: A case study for Georgia, USA*, *Renewable and Sustainable Energy Reviews*, 15 (2011) 2310-2321.
- [19] R. Langton, L.M. Davies, B.E. Scott, *Seabird conservation and tidal stream and wave power generation: Information needs for predicting and managing potential impacts*, *Marine Policy*, 35 (2011) 623-630.
- [20] A.B. Gill, *Offshore renewable energy: ecological implications of generating electricity in the coastal zone*, *Journal of Applied Ecology*, 42 (2005) 605-615.
- [21] O. Langhamer, D. Wilhelmsson, J. Engström, *Artificial reef effect and fouling impacts on offshore wave power foundations and buoys - a pilot study*, *Estuarine, Coastal and Shelf Science*, 82 (2009) 426-432.
- [22] S.A. Abbasi, N. Abbasi, *The likely adverse environmental impacts of renewable energy sources*, *Applied Energy*, 65 (2000) 121-144.
- [23] S. Dolman, M. Simmonds, *Towards best environmental practice for cetacean conservation in developing Scotland's marine renewable energy*, *Marine Policy*, 34 (2010) 1021-1027.
- [24] P.K. Probert, R. Mitchell, *Environmental Implications of Wave Energy Proposals for the Outer Hebrides and Moray Firth*, *Ocean Engineering*, 10 (1983) 459-469.
- [25] O. Langhamer, K. Haikonen, J. Sundberg, *Wave power--Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters*, *Renewable and Sustainable Energy Reviews*, 14 (2010) 1329-1335.
- [26] S.P. Neill, E.J. Litt, S.J. Couch, A.G. Davies, *The impact of tidal stream turbines on large-scale sediment dynamics*, *Renewable Energy*, 34 (2009) 2803-2812.
- [27] P. Breeze, *Ocean power*, in: *Power Generation Technologies*, Newnes, Oxford, 2005, pp. 204-218.
- [28] Y. Lamadrid-Rose, G.W. Boehlert, *Effects of cold shock on egg, larval, and juvenile stages of tropical fishes: Potential impacts of ocean thermal energy conversion*, *Marine Environmental Research*, 25 (1988) 175-193.
- [29] M.A. Shields, L.J. Dillon, D.K. Woolf, A.T. Ford, *Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, UK)*, *Marine Policy*, 33 (2009) 635-642.
- [30] D.L. Millar, H.C.M. Smith, D.E. Reeve, *Modelling analysis of the sensitivity of shoreline change to a wave farm*, *Ocean Engineering*, 34 (2007) 884-901.
- [31] A. Palha, L. Mendes, C.J. Fortes, A. Brito-Melo, A. Sarmiento, *The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices*, *Renewable Energy*, 35 (2010) 62-77.
- [32] G. Suter, S. Bartell, *Ecosystem-level Effects*, in: G. Suter (Ed.) *Ecological Risk Assessment*, Lewis Publishers, Michigan, 1993.
- [33] H.J. De Lange, J. Lahr, J.J.C. Van der Pol, J.H. Faber, *Ecological Vulnerability in Wildlife: Application of a Species-Ranking Method to Food Chains and Habitats*, *Environmental Toxicology and Chemistry*, 29 (2010) 2875-2880.
- [34] P.J. Sydelko, I. Hlohowskyj, K. Majerus, J. Christiansen, J. Dolph, *An object-oriented framework for dynamic ecosystem modeling: application for integrated risk assessment*, *The Science of The Total Environment*, 274 (2001) 271-281.
- [35] G. Holmes, R.W. Johnstone, *Modelling coral reef ecosystems with limited observational data*, *Ecological Modelling*, 221 (2010) 1173-1183.
- [36] G. Hegemann, C. Cocklin, R. Cressey, S. Dupois, A. Kennedy, L. Kingsley, W. Ross, H. Spaling, D. Snaker, *Cumulative Effects Assessment Practitioners Guide*, AXYS Environmental Consulting Ltd. and the CEA Working Group for the Canadian Environmental Assessment Agency, Hull, 1999.

